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EVALUATION OF FLEXIBLE PAVEMENT OVERLAYS

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL
FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

FEBRUARY, 1965

UNIVERSITY OF ALBERTA
FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read,
and recommend to the Faculty of Graduate Studies for
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Date

April 1965

ABSTRACT

The aim of this investigation was to evaluate the effect of a lower bituminous layer in an overlay pavement system.

The evaluation was made from a qualitative comparison of the reactions of an overlay system, when subjected to a static load, to those of a conventional system when subjected to the same loading.

Maximum deflections were measured and used for calculation of the modular ratio and radius of curvature of longitudinal deflection bowls. The maximum deflections and the radii of curvature were determined at the interfaces of the various layers of the pavement structures.

The results of the investigation indicated that, because of the lower bituminous layer in the overlay structure, the overlay structure was stiffer, and therefore less affected by applied loads, than the conventional structure.

The major conclusion was that a bituminous layer, when located at depth in an overlay pavement structure, is a superior structural component than granular subbase at the same depth.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Associate Professor K.O. Anderson, of the Department of Civil Engineering at the University of Alberta, Edmonton, for his guidance and encouragement in the preparation of this thesis.

Special gratitude is also extended to Mr. L.T. Holmes, Deputy Minister of the Saskatchewan Department of Highways and Transportation, for the time, equipment, and personnel required for the field testing part of this program. In particular, the guidance and advice from Mr. W.A. Sheard, Construction Engineer, and Mr. W.E. Winnitoy, Materials and Research Engineer, and their staff was of considerable assistance.

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TERMINOLOGY

The following terminology is applicable to this investigation:

AASHO - American Association of State Highway Officials.

CGRA - Canadian Good Roads Association

Conventional Structure - a pavement structure consisting of a bituminous surfacing layer over a granular layer.

Deflection - the vertical movement caused by an applied load.

Deflection Bowl - the longitudinal (parallel to highway center line) profile of a deflection pattern of an elastic layer.

Elastic Deformation - deformation which disappears, completely and instantaneously, after the load which caused the deformation is removed.

Homogeneity - possessing identical elastic properties at every point within a mass in identical directions.

Hooke's Law - ratio between stress and corresponding strain is constant for all stresses below the elastic limit.

Infinite Dimensions - of infinite dimension in the vertical, lateral, and longitudinal planes.

Isotropy - possessing identical elastic properties throughout a mass and in every direction through any point of it.

Modular Ratio - ratio of the modulus of elasticity of one layer to that of an adjacent layer.

Modulus of Elasticity - ratio of unit stress to unit strain for any value of stress below the elastic limit.

Overlay Structure - a pavement structure consisting of a bituminous surfacing layer over a granular layer, with both layers over a bituminous layer.

Pavement Structure - all layers above the subgrade.

Pavement System - all layers, including the subgrade.

Plastic Deformation - deformation which remains after the load which caused the deformation is removed.

Radial Distance - the longitudinal distance from the center of a loaded area to the point of deflection measurement.

Radius of Curvature - the radius of the curved portion at the center of a deflection bowl.

Semi-infinite Dimensions - of finite dimension in the vertical plane and infinite dimension in the lateral and longitudinal planes.

Strain - change of length per unit of length in a given direction.

Stress - force per unit area.

WASHO - Western Association of State Highway Officials.

CHAPTER I

INTRODUCTION

Agencies concerned with the construction of highways are faced with the problem of resurfacing existing pavements. In Saskatchewan, the province in which this investigation was performed, for example, approximately 200 miles of existing pavement will require resurfacing within the next five years. In many cases, a simple increase in the thickness of the bituminous surfacing layer will be sufficient but in many other cases, a base course will be required between the existing and the new bituminous layers.

Methods for determining the required thickness of overlay pavement structures are numerous and range from that of 'experience' to that of a detailed structural analysis. While use of 'experience' as a thickness design method is diminishing, use of methods based on theoretical principles and practical studies is increasing.

Much work has been performed on the use of deflections and related characteristics for establishing a performance rating, bearing capacity, or relative strength of a pavement system. However, little use of deflections to analyse the reactions of the individual layers of a pavement system to an applied load has been made to date. The purpose of this investigation is to use such data to compare a granular subbase layer in a conventional system with a bituminous layer at equivalent depth in an overlay system and thereby evaluate the value of the lower bituminous layer.

The systems were subjected to a static loading test. During this test, measurements of deflections and deflection bowls were taken at interfaces within the systems and, from these characteristics, calculations of modular ratios and radii of curvature were made. A comparison of the results enabled an evaluation of each system to be possible.

The results are used for a qualitative rather than a quantitative comparison because of the numerous assumptions and approximations associated with the methods

of analysis used. The comparison indicated that the lower bituminous layer in the overlay system provides greater benefit to the system than does granular subbase to a conventional system.

CHAPTER II

THEORETICAL CONSIDERATIONS

General

Studies of the reactions of a pavement structure to imposed loads have now reached the stage where individual layers of the structure, rather than the structure as a unit, are being investigated. Initially, the design of a structure was based on various assumptions and after these assumptions had been subjected to service, the design basis became that of 'experience'.

With the increasing use of flexible pavements came investigations into the theoretical principles behind the reactions. At first, for simplicity, the structure was classed as an ideal soil and internal stresses caused by loads applied to the surface were analysed by the Boussinesq equation (1)*. This equation, based on assumptions that the structure possessed homogeneity, isotropy, continuity, and

(* Numbers in the parentheses refer to references noted in the List of References.)

perfect elasticity, permitted calculation of normal stresses within the structure by:

$$\nabla_z = \frac{3P}{2\pi z^2 \left[1 + \left(\frac{r}{z}\right)^2\right]^{2.5}} \quad (1)$$

wherein:

∇_z	=	normal stress at any point, in pounds per square inch
P	=	applied load on surface, in pounds
z	=	depth to point, in inches
r	=	radial distance to point, in inches

EQUATION 1 indicates that the stress at any point within a structure is dependent on the depth and radial distance to that point but not on the physical characteristics of the materials comprising the structure.

A flexible pavement structure may consist of several layers of compacted or non-compacted, stabilized or non-stabilized soils, each layer of which may possess characteristics which differ from those of any other layer. Therefore, the structure as a unit does not meet the assumptions on which EQUATION 1 is based, and for this

reason, the equation is rarely used for analysis of layered systems.

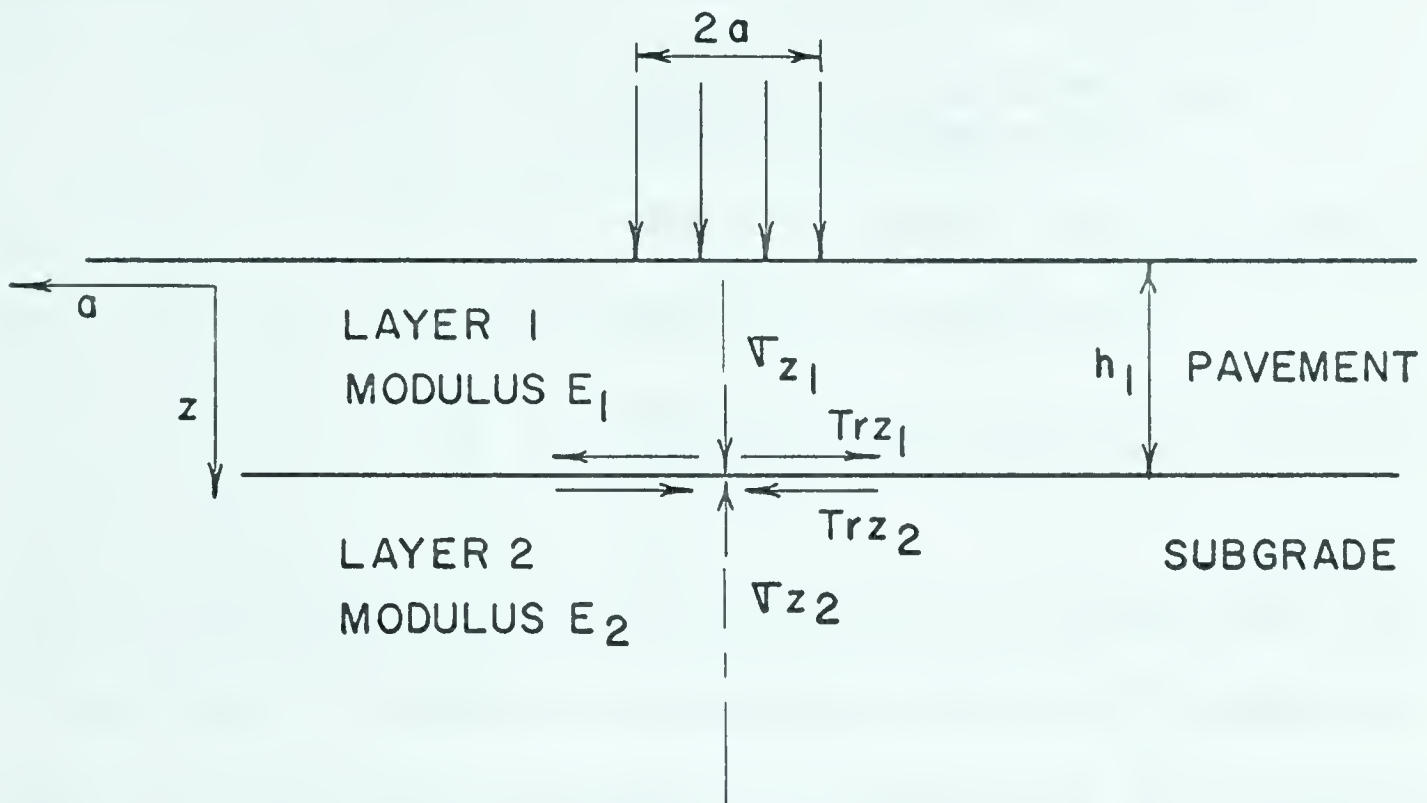
For an individual layer, EQUATION 1 is relatively more acceptable. Controlled production of the materials forming the layer and controlled construction of the layer gives a high degree of homogeneity and continuity in the layer. With the use of suitable constants in the equation, the assumption regarding isotropy can be met. The assumption that the layer is perfectly elastic is not entirely valid.

The materials in a pavement structure are not perfectly elastic because they do not obey Hooke's law and possess a constant ratio of stress to strain over a wide range of stress. Rather, the ratio is assumed to be constant over a relatively short range of stresses and, in most cases, this range is minute. Thus, from a theoretical consideration, a layer in a flexible pavement structure is not perfectly elastic. However, from a practical consideration, for a single application of a moving wheel load, the degree of elasticity of a layer is sufficiently high for the theory of elasticity to be applicable (2).

Some of the earliest work with the theory of elasticity as applied to flexible pavements was performed by Burmister (3). Burmister developed equations for the deflection of the surface of a pavement structure when a uniformly distributed circular load was applied to that surface. The system was assumed to have two layers, one a pavement structure of semi-infinite dimensions and the other a subgrade of infinite dimensions. It was also assumed that the materials in both layers were homogeneous, isotropic, elastic, and possessed a Poisson's ratio of 0.5; that there was continuous contact at the interface between the layers; and that no stresses existed outside the loaded area. FIGURE 1 shows Burmister's assumed conditions.

With these assumptions, the deflection of a surface directly under the center of a loaded area can be determined by:

$$\Delta = \frac{1.5 p a F}{E_s} \quad (2)$$



AT THE SURFACE : $\sigma_z = \tau_{rz} = 0$

AT $z = \infty$ $\sigma_z = \tau_{rz} = 0$

AT THE INTERFACE :

$\sigma_z = \sigma_z = \text{VERTICAL STRESS}$

$\tau_{rz} = \tau_{rz} = \text{SHEAR STRESS}$

$w_1 = w_2 = \text{VERTICAL DEFLECTIONS}$

$u_1 = u_2 = \text{HORIZONTAL DISPLACEMENTS}$

FIGURE 1: BOUNDARY AND CONTINUITY CONDITIONS OF STRESS AND DISPLACEMENT FOR A TWO-LAYER SYSTEM.

(FROM BURMISTER, H.R.B., 1943)

wherein:

Δ	=	surface deflection, in inches
p	=	intensity of applied load, in pounds per square inch
a	=	radius of loaded area, in inches
F	=	deflection coefficient
E_s	=	modulus of elasticity of subgrade, in pounds per square inch

The coefficient, F , is a function of two parameters, the ratio of pavement structure thickness to radius of loaded area, h/a , and the ratio of moduli of elasticity of the pavement structure and subgrade, E_p/E_s , and is indicative of the reaction of a two-layer system to an applied load. As these parameters increase in magnitude, the stress within the system decreases. FIGURE 2 shows these conclusions graphically.

FIGURE 2 indicates a pronounced vertical stress reduction in the upper layer as the modular ratio increases. In accordance with the theory of elasticity, there must be a high shear stress increase in the upper layer to offset this vertical stress loss. These shear stresses, and the shear strength required to balance the stresses, cannot occur in

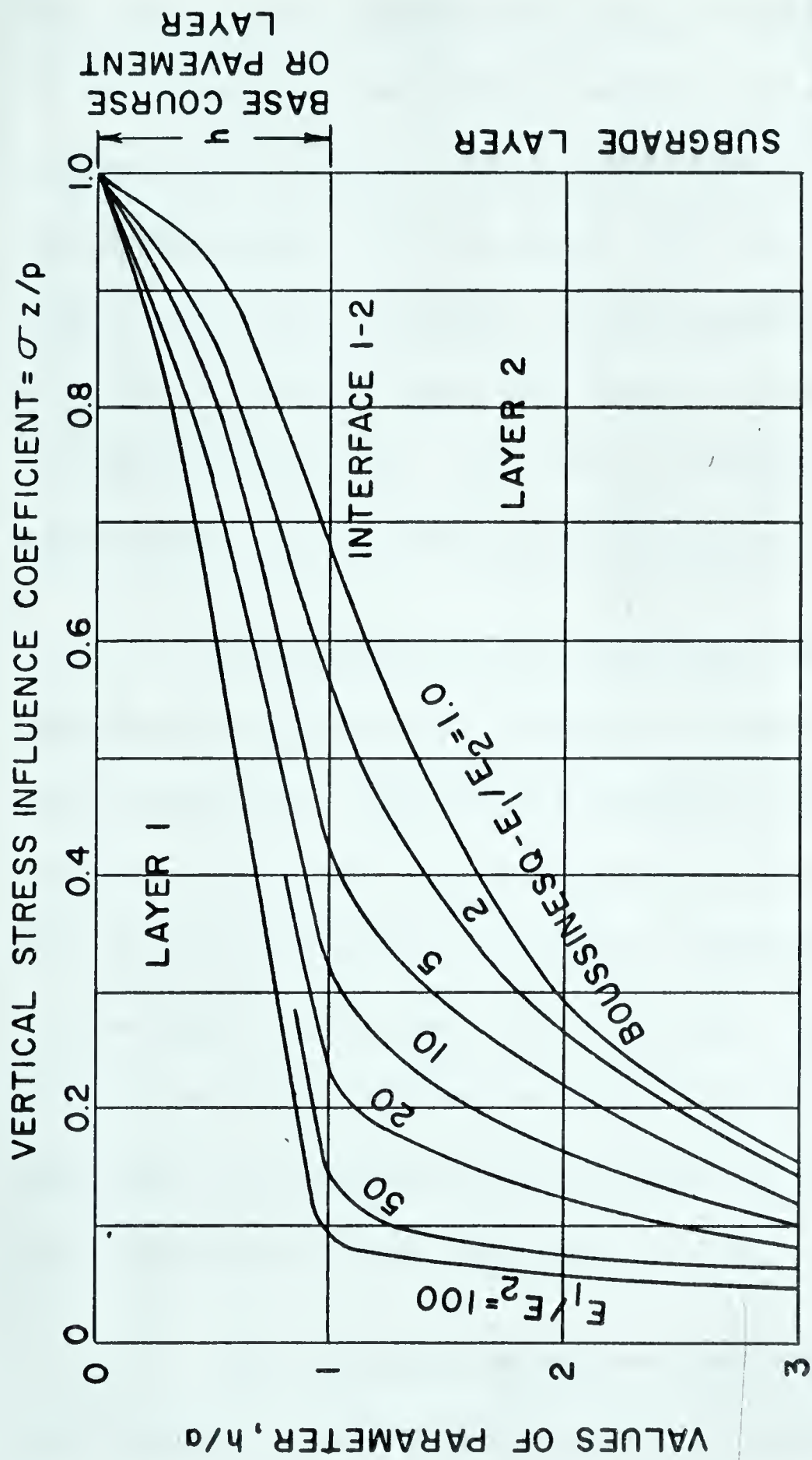


FIGURE 2: BASIC PATTERN OF BURMISTER TWO-LAYER STRESS INFLUENCE CURVES

(FROM BURMISTER, HIGHWAY RESEARCH BOARD BULLETIN 177)

the upper layer unless shear displacements have occurred in that layer. These displacements are achieved by the deflecting of the entire pavement system under an applied load. Burmister (3) has shown that the thickness of the upper layer and the nature of the material comprising that layer are two important factors controlling the stress accumulation. (For more information on the application of the theory of elasticity, see reference (4)).

An analysis of the reactions of a flexible pavement structure thus requires a deflection study of that structure. Burmister's original concept has been the keystone for such studies by showing that, for a constant h/a value, deflection is reduced considerably by an increase in the E_p/E_s value and, for a constant E_p/E_s value, the deflection characteristics of the layered system can be improved by increasing the thickness of the upper layer in the region of h/a less than 1.0 (4).

The original layered-system expressions were for two layers, the bituminous surfacing combined with the granular base course for the upper layer and the subgrade the lower layer. For values of the controlling parameters,

Fox (5) produced tables of stresses for such a system.

Burmister (6) realized that characteristics of bituminous surfacing material differed considerably from those of granular material and expanded his expressions to suit a three-layered system. Acum and Fox (7) developed tables of factors, for normal and radial stresses at layer interfaces, for values of two dimensional parameters and two modular parameters. Schiffman (8), using fixed values for the modular parameters and varying values for the dimensional parameters, developed numerical solutions for normal and shear stresses at the upper interior interface and for the deflection at the surface of a three-layer soil system. Mehta and Veletsos (9) solved Burmister's equation for stresses and displacements at various depths and radial distances within an elastic layered system. Jones (10) expanded Acum and Fox's work to include a wider range of values for the parameters.

Thus, use of the theory of elasticity for general analysis of a flexible pavement structure is well-developed and forms a firm basis for a study of specific characteristics of the structure.

Elasticity of a Pavement System

Burmister assumed that a flexible pavement structure possessed a high degree of elasticity, and field studies have substantiated that assumption. (For the purposes of this investigation, a perfectly elastic system is assumed to be one which, after having been deformed by an applied load, resumes its original shape, completely and instantaneously, after removal of the load which caused it to lose that shape.) Hveem (11) has stated that, for the single application of a moving wheel load on a pavement surface, the deflection of that surface is 99.9 per cent elastic.

Baker and Papazian (12) have stated that a deflection study of a pavement system should be split into consideration of elastic and non-elastic deflections. In their view, a theory of visco-elasticity rather than one of pure elasticity is more appropriate to flexible pavement conditions. Their work, and that of Monismith and Secor (13), has shown that the strain of an asphalt pavement layer is not perfectly elastic but time and temperature dependent.

Deflections in a Pavement System

A key relationship to be determined in the analysis of the actions and reactions of a pavement structure under loading is that of stress-strain of the materials forming the structure. If the reactions do not accommodate the loading, distress may occur. Thus, determination of the stress-strain properties of the pavement structure and of the individual layers is of importance in understanding pavement behaviour.

Because stress in a pavement structure is difficult to measure, stresses are generally calculated from an analysis of strains. The strains may be determined from easily measured deflections resulting from an applied load. Burmister's (3) original equations, which led to the acceptance of the treatment of flexible pavement structures as layered systems, were developed from deflection and plate-bearing studies.

As shown previously, Burmister's expressions indicate that deflection is governed by the wheel load and the area over which it acts, the subgrade modulus and the

modular ratio of the component layers, and the ratio of the loaded area to the pavement structure thickness. The modular factors in turn are dependent on the material which form the layers. The reactions of the subgrade and base course are functions of such soil properties as moisture content, density, and soil particle shape and arrangement while the reactions of the asphalt surfacing are functions of the asphalt content, type, age, and temperature. These properties are of secondary importance in analysing general reactions of a pavement structure and are not examined herein.

Deflection measured at a pavement surface is an accumulation of deflections from each of the component layer surfaces but, for heavy wheel loads, the subgrade layer contributes most to the gross deflection (14). The magnitude of the gross deflection is controlled by the 'stiffness' of the system as a unit and on the relative stiffness, similar to Burmister's E_p/E_s modular ratio, of adjacent layers but not directly on the elastic properties of the pavement structure (12).

The effect of stiffness on pavement structure reactions has been shown by Burmister (15) from the general results of the WASHO road test. It was necessary for the pavement system to deflect in order to mobilize shear stresses at the layer interfaces and impart shear strength to the structure. Burmister concluded that:

- the effectiveness of a layered system in distributing vertical stresses over a subgrade is greatly reduced by an increase in the dimensional ratio, h/a , but at a less rapid rate for pavements with larger modular ratios E_p/E_s . Thus, with a constant thickness of the pavement structure, the effectiveness of the layered system in reinforcing the subgrade decreases with decreasing tire size.
- the higher the shear stresses that can be sustained at an interface, the greater is the reinforcing action and stiffness of the layered system.
- for a constant h/a ratio, the load-deflection responses of a layered system are improved with an increase in E_p/E_s .
- for a constant radius of loaded area, the greatest improvement in a layered system can be achieved by

increasing the thickness of the upper layer to a value corresponding to $h/a = 1.0$, after which the layered system becomes less effective and Boussinesq's equations become applicable.

The above evaluations have been supported, in part, by several research projects. Brown (16) analyzed plate bearing tests on airfield pavements and concluded that deflections under small diameter loadings are controlled by properties of the asphalt surfacing and the base course, whereas deflections under large diameter loadings are controlled by the subgrade modulus. Benkelman and Williams (17), from the results of the Hybla Valley test road, also concluded that deflection varied as a linear function of the applied load and as the diameter of the loaded area. Skok and Finn (18), from an evaluation of the AASHO road test results, concluded that stress on a subgrade decreased as the stiffness of the upper layers increased and as surface thickness increased. The relative effect of surface strength and surface thickness on stress reduction increased as subgrade strength increased.

To summarize the effects of relative stiffness of the component layers on pavement deflection, it may be said that, for given structural dimensions, deflections decrease as relative stiffnesses increase. The physical properties of the layers, the thicknesses of the layers, and the load on the structure determine the relationship between stress and deflection. Yoder's (14) evaluation of the results from the WASHO road test led to the conclusion that, for a given deflection and paving material, stiff subgrades resulted in higher stresses in the surfacing structure than did weak subgrades and, for a given deflection and subgrade, stress in the surfacing structure varied directly with the stiffness of the structure.

Although stiffness of the structure has the most pronounced effect on the magnitude of deflection of the structure, several other factors are also of importance. Speed of the wheel load across a pavement or, in effect, the rate of loading has a definite effect. Yoder (14) and Harr (19) have shown that deflections decrease as vehicle speed increases and that speeds of less than 15 m.p.h. result in the largest deflections. Temperature and hardness of the

asphalt binder have a direct effect on the stiffness of the asphalt surfacing, with the stiffness increasing with a decrease in temperature and an increase in hardness. The number of repetitions of loading affects the deflecting properties, with the magnitude of the deflections increasing with an increase in the number of repetitions. Benkelman and Williams (17), from their study of the Hybla Valley project in which deflections were measured for 75 repetitions, showed that the magnitude of the deflections increased over the first 10 repetitions but remained constant after that. Extensive analyses of deflection data by the CGRA (21) and the AASHO (22) have also supported these conclusions.

Flexure of a Pavement System

Deflections alone, although a vital aid in evaluating pavement performance, may not lead to pavement distress. Dehlen's (23) work on South African highways has indicated that deflection and radius of curvature of the deflection bowl cannot be used as more than indicators of stresses and, of the two, radius of curvature appears to be more accurate. For a given radius of curvature, the flexural stresses increased with an increase in modulus and/or in

thickness. While deflection was controlled by the moduli of all layers, radius of curvature was governed mainly by the moduli of the upper layers. Thin surfacings of less than $1\frac{1}{2}$ inches in thickness appeared to have little effect on deflections or radii but thick mats with a high modulus aided in reducing the deflection and increasing the radius. Other findings by Dehlen were that the radius of curvature was related to the tire pressure but not to wheel load, whereas the reverse was true for deflections; that the radius of curvature of a transverse deflection bowl was shorter than that of a longitudinal bowl; and that the radius was more severe directly under a wheel than between dual wheels. FIGURE 3 shows these last two conclusions.

Herner (24), using mechanical model analyses, found that deflections were in a bowl-shaped pattern with the maximum deflection directly under the wheel load and affected by the loaded area and the pavement thickness. He concluded that a comparison of deflection bowls at equal maximum deflections but at varying loads and thicknesses should be based on shear stresses and resistances.

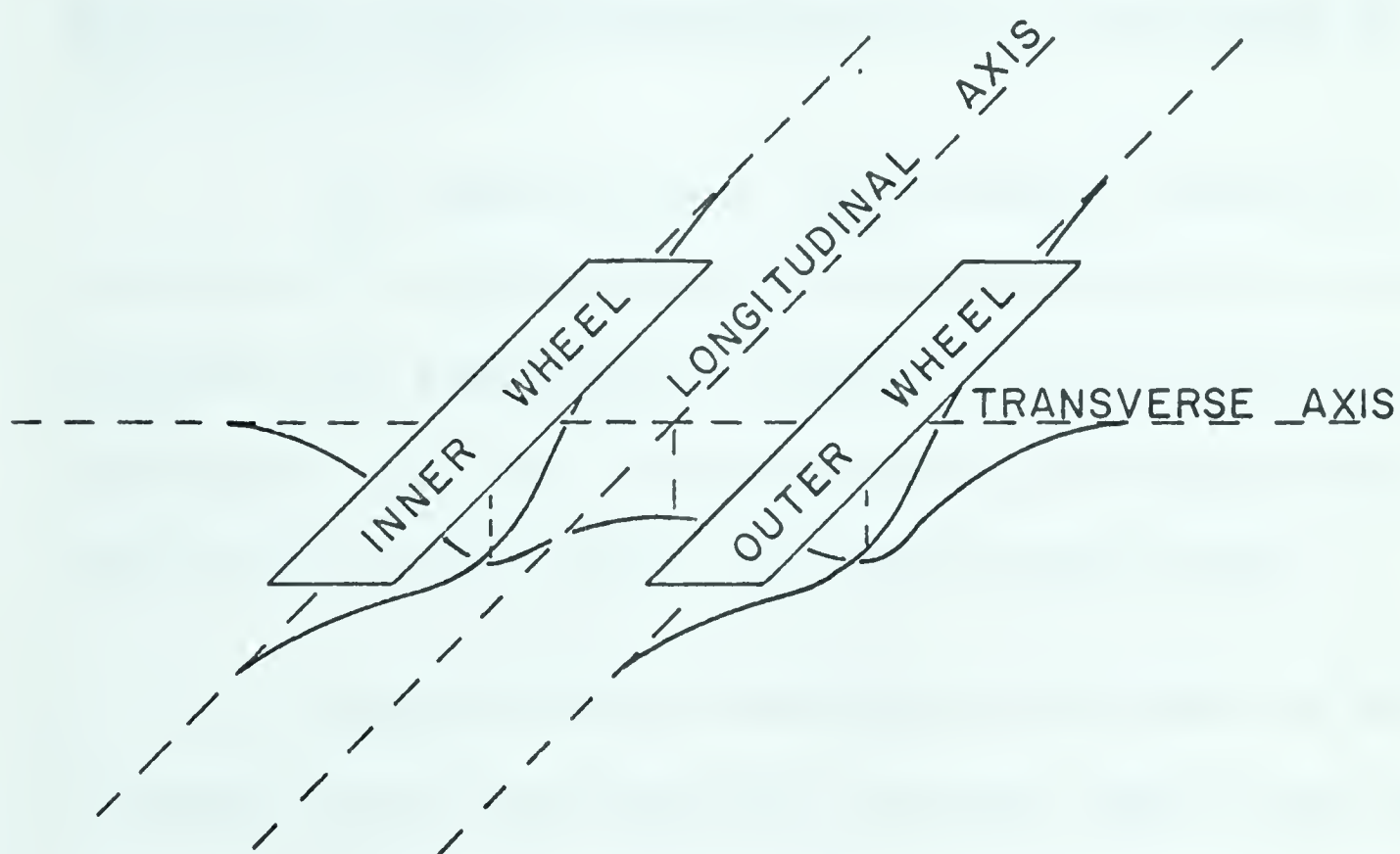


FIGURE 3: DEFLECTION BOWLS UNDER
DUAL WHEEL LOADS

Walker et al (25), from studies of deflections on a controlled test section, concluded that if the major portion of the deflection was in the subgrade, the radius of curvature of the surface bowl would be large; if in the upper layers, the radius would be small.

Application of Theoretical Principles to the Design of Overlay Structures

The application of the preceding theoretical principles to the design of overlay structures on flexible pavements has been meagre. However, several facets of the principles, and their relationship to a structure with a stabilized interior layer, have been investigated.

Schnitter (26) investigated the effect of placing a cement-treated base beneath a granular base on two Swiss airfields. He concluded that because the surface deflections and the subgrade stresses were lower in a structure with a stabilized layer in the lower level, that structure was superior to one with a stabilized layer in the upper level.

Gonella and Font (27), from deflection studies on overlays of a special design, concluded that surface deflection

decreased as thickness of the overlay increased.

Brown (16), from an analysis of the results of plate bearing tests on airfield pavements, concluded that the modulus of elasticity of an overlay structure was higher than that for a conventional structure because the existing surfacing provided a firm base for the compacting of the overlay layers.

Zube and Bridges (28), from an extensive analysis of deflections on layer surfaces during construction of several overlay structures, determined deflection-reduction capacities of soil-cement base courses and of asphaltic concrete surface courses on pavement structures of various total thicknesses.

McLeod (29), from plate bearing studies, concluded that an old asphalt surface will be stronger than the same thickness of the new mat because of the effects of age, traffic compaction, and maintenance.

The CGRA (21), from an investigation of the Benkelman beam and deflections, related deflections to plate bearing

loads. From this investigation, an overlay design procedure based on a required thickness of granular material to limit the surface deflection to a specified limit was developed.

Thus, it appears that little, if any, investigations have been conducted to determine the deflection characteristics within an existing pavement structure under actual conditions, or to subject the theoretical principles of layered system actions to an overlay structure.

Summary

To summarize the reactions of a flexible pavement structure to an applied wheel load, it may be said that the efficiency of a structure in resisting the effects of the load is governed by the strength and the flexibility characteristics of the structure and the component layers. The strength function provides a control on the deflections and, therefore, the shear strength and the load transmission ability of the various layers. The flexibility function governs the development of shear strength and the ability of the structure to withstand repeated loadings.

CHAPTER III

INVESTIGATION METHODS

Details of Test Section

The highway used as a test section for this investigation is a major trans-provincial route of Saskatchewan. The conventional system is located on Highway 39, between Estevan and Midale, and is hereinafter designated section 39-3. The overlay system used for direct comparison with the conventional system is also located on Highway 39, between Weyburn and Corinne, and is hereinafter designated section 39-5/6.

The highways tested were constructed in accordance with accepted practices for such procedures as compaction, aggregate selection, and strength testing and control. Although the structures are of similar total thickness, the thicknesses of the component layers varied considerably. Since this investigation is based on a comparison of structures rather than of individual layers, these variations

are not considered as important. The major difference between the structure components is that of the presence of the lower bituminous layer in the overlay structure.

The subgrade soils are of difference classification but possessed similar C.B.R. values at the time of construction. With this similarity, and with an assumption that both subgrades have been subjected to identical climatic conditions over a number of years and have therefore reached a moisture condition approaching equilibrium, the subgrades are assumed to have similar strength characteristics. No destructive procedures for moisture content or density testing were performed on the subgrades.

(Figures showing the geographical location of the test section and the physical characteristics of the pavement systems are contained in APPENDIX A.)

Six locations were selected for the conventional structure and ten for the overlay structure. The locations were randomly placed longitudinally and consecutively alternated between driving lanes. At each location, two points were selected for detailed testing and the average of the results

for the pairs of points was taken as being applicable to the location. The average of the results for the locations was taken as being applicable to the structure.

Measurement of Deflections

Measurement of deflections was by the procedure proposed by the CGRA Special Committee on Pavement Design and Evaluation (21). This procedure measures rebound movements as the load is removed rather than true deflections as the load is applied. However, because the results were used on a qualitative basis only, the terms "deflection" and "rebound deflection" have been used without differentiation in this investigation. The measurement of deflections for deflection bowl patterns required modifications to the standard CGRA procedure and these modifications, and the revised procedure, are contained in APPENDIX B.

The CGRA (21) procedure requires that measured deflections, called "apparent deflections," be corrected to account for interference of the deflecting surface on the measuring apparatus. Tests conducted in Saskatchewan have shown that the apparatus is not so affected on major highways

during the late fall season. Thus, this correction was not applied in this investigation.

The CGRA (21) procedure requires that measured deflections be corrected for the effects of temperature on a bituminous mat. The correction to be applied is 0.002 inches for each 10° Fahrenheit difference in mat temperature from 70° Fahrenheit. This correction was applied in this investigation.

Measurement of deflections within the structures required the development of a special probe, details of which are contained in APPENDIX B.

Deflections for this investigation were measured in late fall of 1962 for the overlay section and in late fall of 1963 for the conventional section. Deflections between 1960 and 1963 on these two sections exhibited a consistent trend, with the difference in gross deflection being approximately 0.002 inches and the magnitude of the gross deflection being approximately 0.030 inches.

Calculation of Modulus of Elasticity

The modulus of elasticity of a pavement system may be determined from 'static' methods such as plate-bearing tests or deflection bowl measurements or from 'dynamic' methods such as vibration measurements. The method used in this investigation was one proposed by Shields and Hutchinson (31) and which requires deflection bowl measurements.

The systems are assumed to be two-layered, with the upper layer being the pavement structure and the lower layer the subgrade. The moduli are calculated from two points on a surface deflection bowl. With these deflection values and with EQUATIONS 3, 4 and 5, the modular ratio of a system can be found from FIGURE C-1 and the central deflection coefficient from FIGURE C-2. (The curves are shown in APPENDIX C and were extrapolated to fit the thickness required by assuming the same shape of curve would be applicable for each inch increase in thickness and that each curve would be separated by an equal change. For the small modular ratios of this investigation, this extrapolation is reasonable.)

$$W_O = C_O \frac{p \times a}{E_p} \quad (3)$$

$$W_H = C_H \frac{p \times a}{E_p} \quad (4)$$

$$\frac{W_O}{W_H} = \frac{C_O}{C_H} \quad (5)$$

wherein:

W_O = deflection of surface at center of loaded area, in inches.

W_H = deflection of surface at a radial distance equal to the thickness of the pavement structure, in inches.

C_O = deflection coefficient at center of loaded area.

C_H = deflection coefficient at radial distance equal to thickness of structure.

p = intensity of applied load, in pounds per square inch.

a = radius of loaded area, in inches.

The pavement modulus is determined from EQUATION 3 and the subgrade modulus from the modular ratio.

This procedure is repeated for a radial distance of twice the thickness of pavement structure. The average of the pavement moduli found by these two procedures is

taken as the modulus of elasticity of the pavement structure.

Similarly, the modulus for the subgrade is determined.

(Sample calculations for the moduli determinations are contained in APPENDIX C.)

Calculation of Radius of Curvature

The exact radius of curvature of a deflection bowl of a pavement system layer is difficult to calculate because the exact shape of a bowl is highly variable. The shapes commonly assigned to deflection bowls are circular, parabolic, or that of a sine curve.

For this investigation, the shape is assumed to be circular with a radius determined by:

$$R = \frac{6004.8}{\Delta_p} \quad (6)$$

wherein:

R = radius of curvature of center of deflection bowl, in feet

Δ_p = difference in deflection at a radial distance of 12 inches and at the center of the deflection bowl, in thousandths of an inch.

The portion of the circle bounded by a chord length of 24 inches was assumed to contain the shortest radius of curvature within the entire deflection bowl.

(Development of this equation, and sample calculations with it, is contained in APPENDIX C.)

Summary

Although extensive calculations have been performed to determine numerical values for the properties under investigation, little emphasis is placed on these numbers because of the numerous assumptions and arbitrary procedures used in finding them. The numerical values are used for qualitative comparison purposes only.

Although the systems under investigation are composed of more than two layers, the analyses for moduli of elasticity are based on the assumption that the systems are two-layered. However, because the investigation is concerned with qualitative results only, the two-layered analyses are sufficiently accurate and the refinement required for a multi-layered system is not justified.

CHAPTER IV

DEFLECTIONS WITHIN LAYERED PAVEMENT SYSTEMS

General

If the reactions of a pavement structure are in accordance with the theory of elasticity, displacements within the various layers are required for shear stresses to be developed and for shear strength to be mobilized. These displacements result from the deflecting of the layers under an applied load.

The amount of deflection required for the mobilization of maximum strength in any layer is dependent upon the properties of that layer. The gross deflection of a system is a function of the layer properties and the interactions between the layers. If the deflections are too large for a particular layer, the stresses may exceed the strengths and the deformations within that layer may change from an elastic nature to a plastic nature.

Because of the large number of variables affecting deflection, it is difficult to assign acceptable deflections for a pavement system. However, theory and practise have shown that deflection is a guide to pavement performance and, for a given system, deflection limits can be established. Numerical values of deflection must be correlated with pavement performance before they can be used as indicators of stress actions. If this is not done, the deflection values become little more than statistics.

The pavement structures used for this investigation possessed similar CGRA performance ratings and were tested under identical loading procedures. It is thus assumed that a comparison of the deflection results can be given emphasis and will have direct meaning.

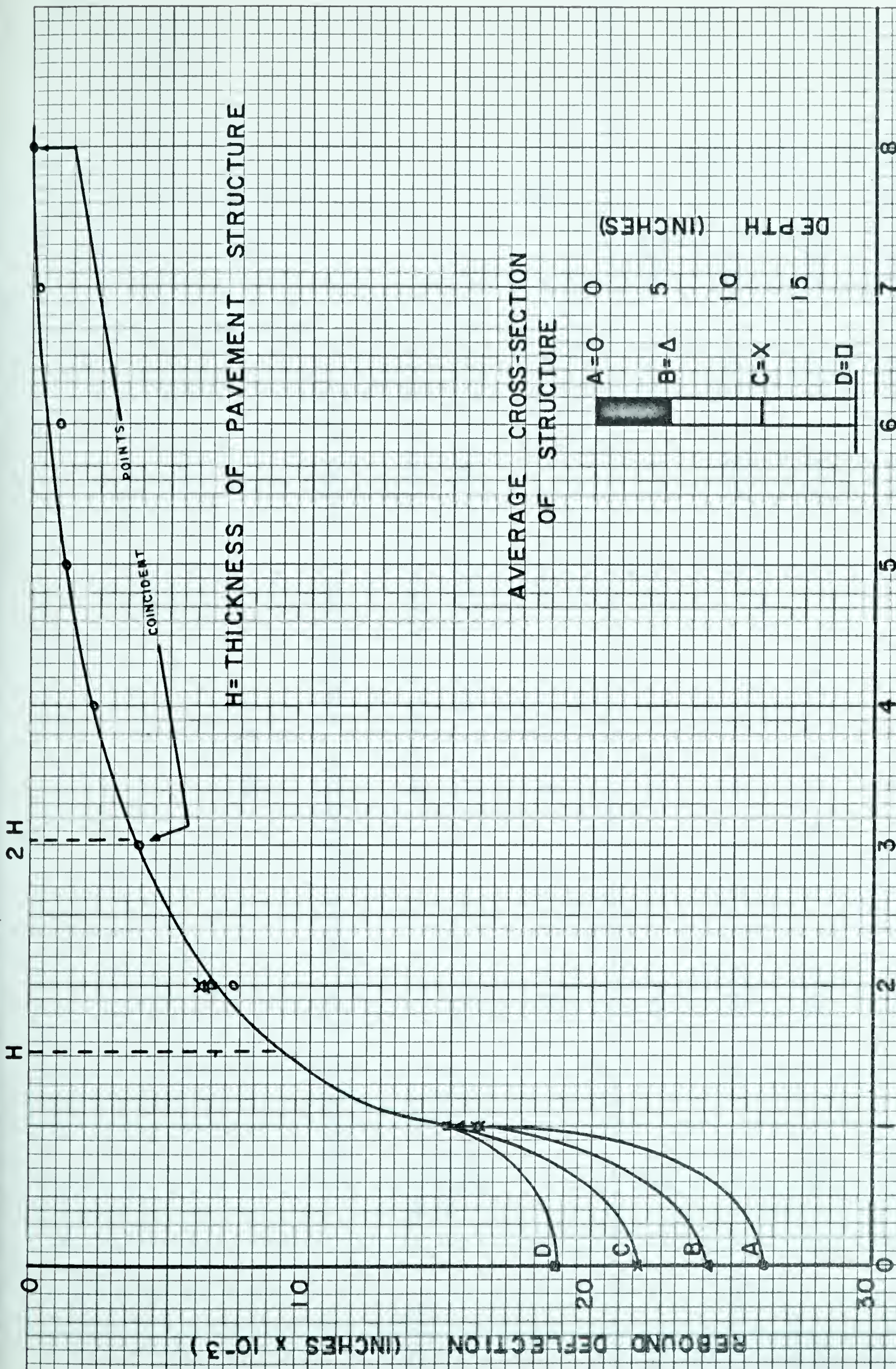
Maximum Deflections within Layered Systems

FIGURES 4 and 5 show the average deflection patterns for the pavement systems under study. These figures represent the deflection patterns measured parallel to the longitudinal axes of the highways and between the dual wheels

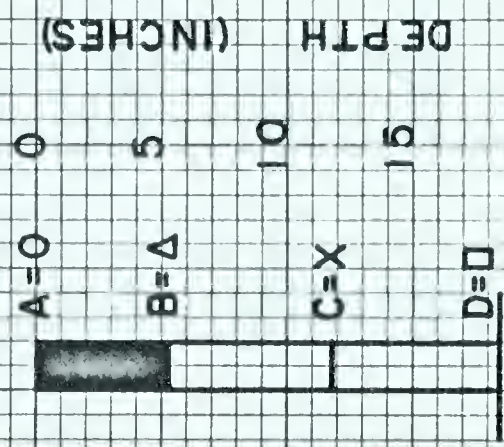
of the loading truck.

The figures show that the maximum deflection for the longitudinal pattern occurred directly under the loaded area and that the surface deflection, or gross deflection, was the maximum deflection within the system. This finding supports that of others and is a logical conclusion. However, because the maximum deflection, regardless of the axis of measurement, occurs directly under the wheels of a dual wheel arrangement (23), (31), rather than between the wheels, the surface deflections discussed herein are somewhat less than true maximums.

FIGURE 4 shows a surface deflection of 0.0261 inches for the conventional pavement cross-section and, of this amount, 0.0188 inches occurred in the subgrade. In other words, 72.0 per cent of the total deflection occurred in the foundation material.



AVERAGE CROSS-SECTION
OF STRUCTURE



RADIAL DISTANCE - PROBE TO LOAD (FEET)

FIGURE 4: AVERAGE LONGITUDINAL DEFLECTION BOWLS,

CONVENTIONAL SYSTEM 39-3

TABLE I
DEFLECTION BOWL CHARACTERISTICS, CONVENTIONAL SYSTEM 39-3

Interface	Radius of Curvature (feet)	Rebound Deflections (inches x 10 ^{-3*})							
		Radial Distance (feet)							
		0	1	2	3	4	5	6	7 8
Surface	566	26.1	16.0	7.3	3.9	2.2	1.2	1.0	0.2 0
Top of Base Course	690	24.2	15.4	6.1	3.9	2.3	1.2	1.0	0.2 0
Mid-base Course	969	21.7	15.9	7.1	3.9	2.2	1.2	1.0	0.2 0
Top of Subgrade	1820	18.8	14.9	6.4	3.9	2.3	1.3	1.0	0.2 0

*Average of 12 deflections

TABLE II

MAXIMUM DEFLECTIONS AT VARIOUS DEPTHS, CONVENTIONAL SYSTEM 39-3

Section	Surface Deflection	Depth to Base Course (inches)	Base Course Deflection	Depth to Mid-Base (inches)	Mid-Base Deflection	Depth to Sub- grade (inches)	Subgrade Deflection
21	25.1	5.4	23.4	10.8	21.6	16.2	17.5
22	22.7	5.1	20.5	12.5	16.3	19.8	14.1
23	23.5	5.1	21.8	11.9	20.0	18.6	18.1
24	28.8	5.7	27.3	12.2	24.8	18.6	21.4
25	30.1	5.1	26.7	11.4	24.0	17.7	21.2
26	26.7	4.8	25.8	12.0	23.4	19.2	20.3
Mean	26.1	5.2	24.2	11.8	21.7	18.4	18.8
Std. Dev- iation	2.7	0.3	2.5	0.5	2.9	1.2	2.5

FIGURE 5 shows a surface deflection of 0.0278 inches for the overlay pavement cross-section, and of this amount, 0.0212 inches, or 76.3 per cent, occurred in the sub-grade.

Results from the AASHO road test (22) have shown a similar finding, with the subgrade responsible for approximately 79 per cent of the total deflection after 800,000 load applications but regardless of wheel load or pavement structure thickness.

One of the assumptions used in developing EQUATION 1 is that the material located above the plane of measurement is incompressible or, in other words, the deflection of the surface of a layer within a structure is equal to that measured at the surface of the structure. The finding that this assumption is invalid provides an explanation as to why measured deflections are generally lower than those calculated from EQUATION 1. Although the invalidity of this assumption is not the only reason for this discrepancy, it is sufficient justification for refutation of this equation for layered system analysis.

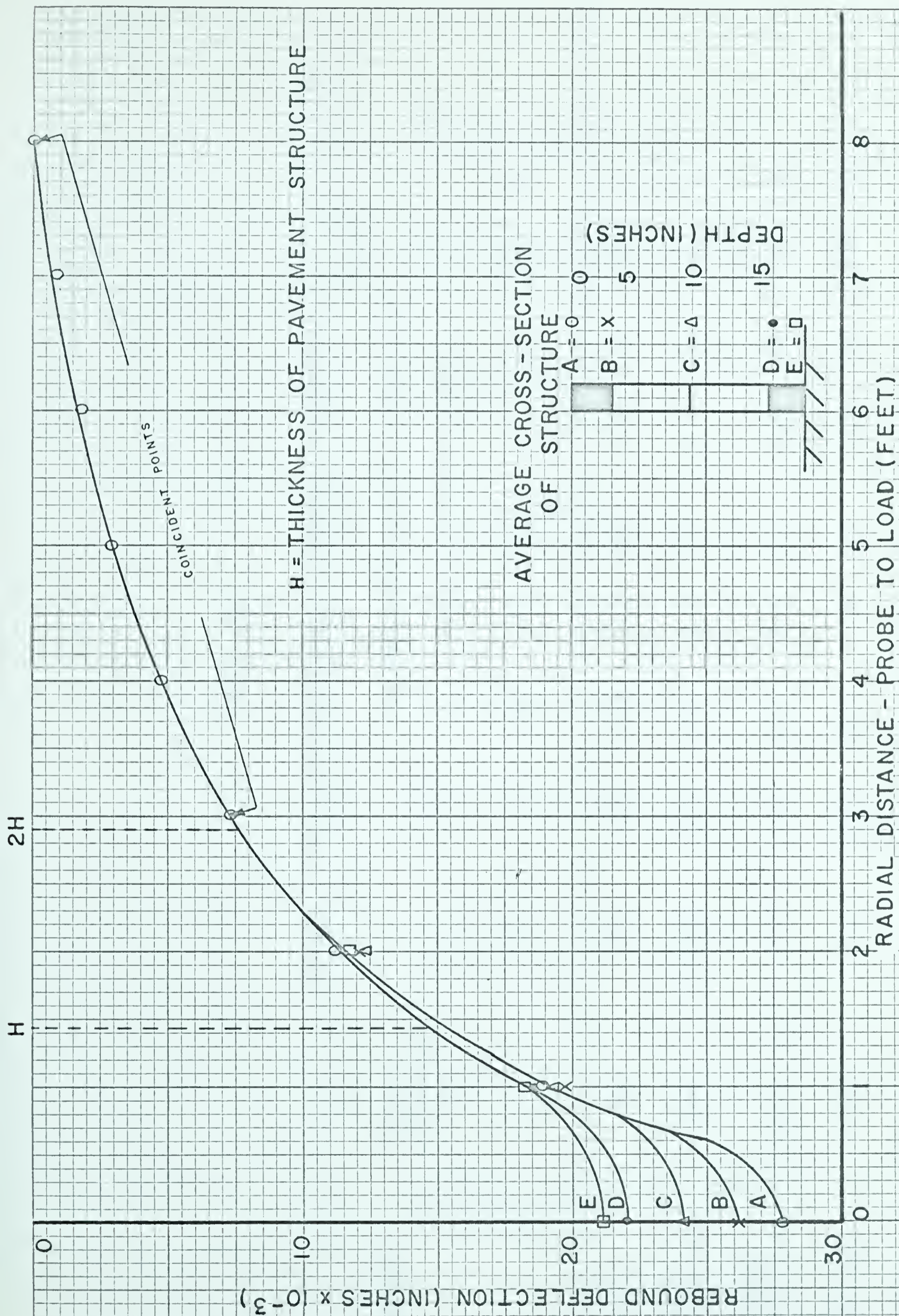


FIGURE 5: AVERAGE LONGITUDINAL DEFLECTION BOWLS,
OVERLAY SYSTEM 39-5/6

TABLE III

DEFLECTION BOWL CHARACTERISTICS, OVERLAY SYSTEM 39-5/6

-3*

Interface Radius of Curvature (feet) Rebound Deflections (inches x 10) Radial Distance (feet)

0 1 2 3 4 5 6 7 8

Surface	682	27.8	19.4	11.4	7.1	4.6	3.0	1.8	0.8	0
Top of Base Course	834	26.2	19.7	11.9	7.3	4.5	2.7	1.6	0.6	0
Mid-Base Course	1155	24.2	19.6	12.3	7.8	4.5	2.8	1.6	0.5	0
Top of Lower Mat	1580	22.1	18.8	12.3	7.6	4.7	2.9	1.5	0.6	0
Top of Subgrade	2071	21.2	18.5	12.2	7.8	4.6	2.8	1.5	0.6	0

*Average of 20 deflections

TABLE IV

MAXIMUM DEFLECTIONS AT VARIOUS DEPTHS, OVERLAY SYSTEM 39-5/6

Section	Surface Deflection	Depth to Base Course (inches)	Base Course Deflection	Depth to Mid-Base (inches)	Mid-Base Deflection	Depth to Lower Mat (inches)	Lower Mat Deflection	Depth to Subgrade (inches)	Subgrade Deflection
11	28.6	3.3	27.9	9.5	27.7	15.8	24.1	18.3	23.4
12	32.0	3.0	34.9	10.5	34.6	18.0	27.8	20.8	29.9
13	19.9	3.3	18.7	9.3	17.6	15.0	15.3	17.8	13.9
14	24.0	3.3	21.1	8.8	20.4	14.3	19.7	17.0	18.4
15	23.0	2.5	20.6	8.0	19.9	13.3	18.6	15.8	16.4
16	25.7	3.5	24.7	8.5	21.7	13.5	19.8	16.3	17.9
17	25.2	3.5	21.9	9.0	20.6	14.5	20.4	17.0	19.4
18	28.9	3.3	28.9	8.8	25.2	14.5	23.8	16.8	22.4
19	29.0	3.3	28.0	8.8	25.7	14.5	24.3	17.0	23.3
20	41.9	3.3	35.6	8.8	30.3	14.5	27.4	17.0	27.2
Mean	27.8	3.2	26.2	9.0	24.4	14.8	22.1	17.4	21.2
Std. Deviation	5.8	0.3	5.7	0.6	5.1	1.2	3.8	1.3	4.7

All deflections in inches x 10⁻³

Comparison of FIGURES 4 and 5 indicates that the overlay structure permitted a larger deflection than the conventional structure. However, the small difference of 0.0017 inches on gross deflection is not statistically significant, according to the standard statistical "t-test". The figures also show that the shapes of the deflection bowls of the conventional system differ from those of the overlay system, a feature that will be discussed in a following chapter.

If, on a hypothetical basis, it is assumed that the difference in gross deflection is statistically valid, the reasons for the difference may have been few but of considerable importance. Because the total thickness of the structures and the methods under which they were constructed and tested were similar, these factors should not have contributed to the difference in gross deflection. The major contributors to the difference may have been variations in the temperature of the bituminous surfacings, or variations in the subgrade conditions, or the presence of the old bituminous surfacing layer at the bottom of the overlay structure.

Effect of Surface Temperature on Surface Deflection

The magnitude of the deflection of a layer is dependent on the stiffness of that layer which, in turn, is dependent on the interactions of the materials comprising that layer. In a bituminous mix, the property most affecting the stiffness of the mix is the viscosity of the asphalt binder.

As the viscosity of the asphalt increases, the stiffness of the mix increases. Factors which affect the viscosity are the grade, age, and temperature of the asphalt. As the age increases and as the grade and temperature decrease, the viscosity increases. For this investigation, the original penetration grade and age of the asphalt in both sections were comparable, leaving temperature as the main variable affecting viscosity.

The Canadian Good Roads Association (21) have concluded that a change of 10° Fahrenheit in mat temperature from a reference standard of 70° causes a change of 0.002 inches in surface deflection, provided that the deflections were measured by the CGRA rebound procedure. The AASHO (22)

road test results have indicated that the surface deflection is increased by an increase in mat temperature up to 80° . At a temperature between 80° and 120° F., temperature appears to have little effect on surface deflection.

FIGURE 6 indicates a temperature correction of 0.002 inches per 10° F., is valid for temperatures up to 75° F. Beyond that value, the temperature effect became insignificant. This finding agrees with that from the AASHO and CGRA, but testing was not performed at temperatures beyond 87° F., and, therefore, there was no check on the AASHO upper limit of 120° F.

From TABLES V and VI, the average of the temperature-corrected surface deflections for the conventional structure is 0.0263 inches and that for the overlay structure is 0.0272 inches, for a difference of 0.0009 inches in favour of the conventional structure. The difference in the non-corrected deflections is 0.0017 inches, also in favour of the conventional structure. The difference related to temperature-corrected deflections is also not statistically significant and it is concluded that the temperature of the

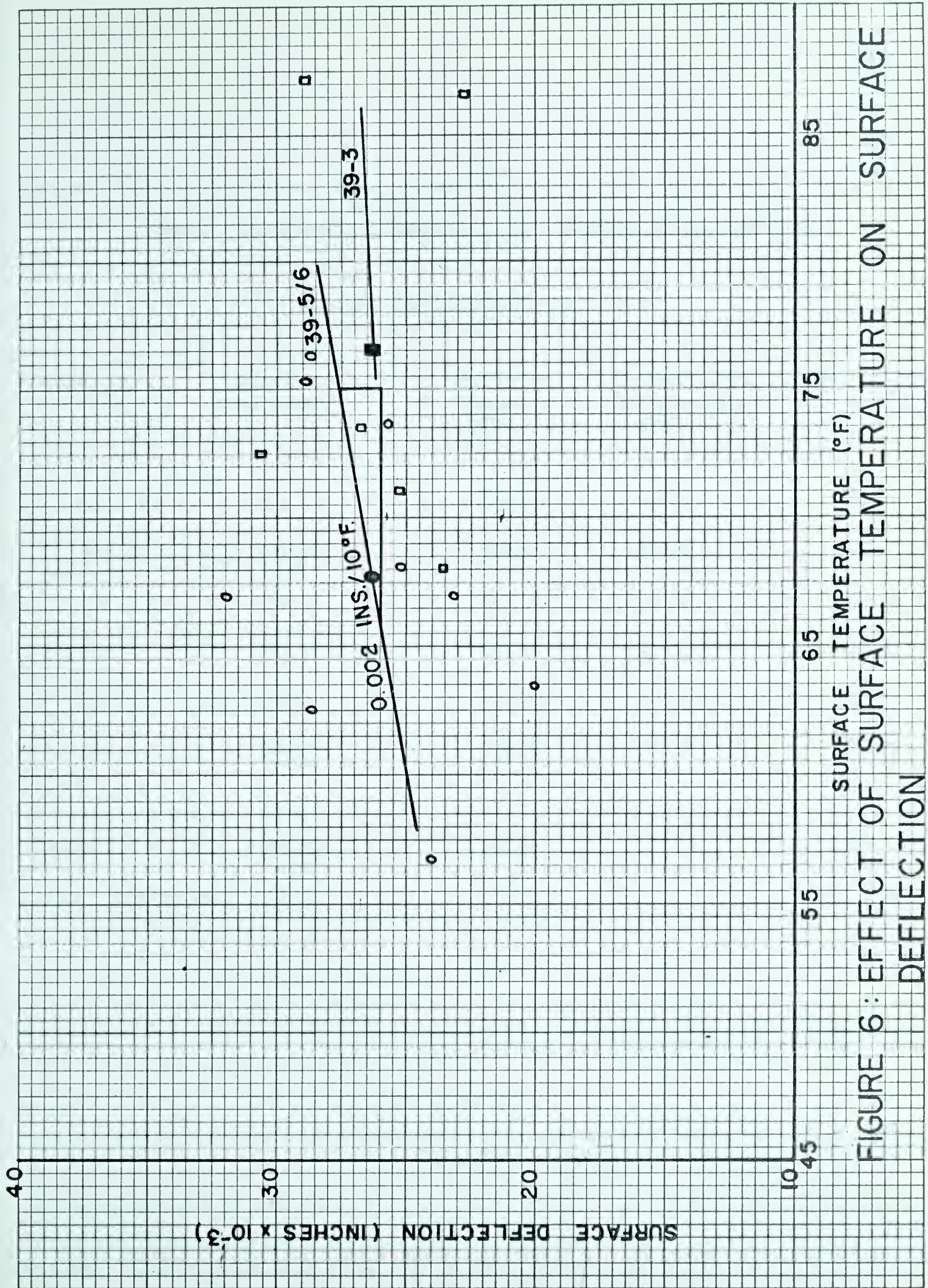


FIGURE 6: EFFECT OF SURFACE TEMPERATURE ON SURFACE DEFLECTION

TABLE V

EFFECT OF SURFACE TEMPERATURE ON SURFACE DEFLECTION

CONVENTIONAL STRUCTURE 39-3

Section	Surface Δ (ins.x10 ⁻³)	Surface Temp. (°F)	Change from 70° Standard (°F)	Corrected Δ (ins.x10 ⁻³)
21	25.1	71.0	+1.0	25.3
22	22.7	86.5	+16.5	22.7
23	23.5	68.0	-2.0	23.1
24	28.8	87.0	+17.0	28.8
25	30.1	72.5	+2.5	30.6
26	26.7	73.3	+3.3	27.4
Mean	26.1	76.4		26.3
Std. Deviation	2.7	7.5		3.2

TABLE VI

EFFECT OF SURFACE TEMPERATURE ON SURFACE DEFLECTION

OVERLAY STRUCTURE 39-5/6

Section	Surface Δ (ins. $\times 10^{-3}$)	Surface Temp. ($^{\circ}\text{F}$)	Change from 70 $^{\circ}$ Standard ($^{\circ}\text{F}$)	Corrected Δ (ins. $\times 10^{-3}$)
11	28.6	62.5	-7.5	27.1
12	32.0	66.9	-3.1	31.4
13	19.9	63.4	-6.6	18.6
14	24.0	56.7	-13.3	21.3
15	23.0	67.0	-3.0	22.4
16	25.7	73.6	+3.6	26.4
17	25.2	68.0	-2.0	24.8
18	28.9	76.3	+6.3	28.9
19	29.0	75.2	+5.2	30.0
20	41.9	66.3	-3.7	41.2
Mean	27.8	67.6		27.2
Std. Deviation	5.8	5.8		6.0

bituminous surfacing could not have been a significant contributor to the difference in gross deflections.

Effect of Subgrade Conditions on Surface Deflection

Little information on the conditions of the subgrade for either the conventional system or the overlay system was available at the time of testing. From the information that was available, which was the general soil classification and the CBR value at the time of surfacing structure design, and the fact that both subgrades had been subjected to similar climatic conditions for at least seven years, an assumption that the subgrades possessed similar strengths at the time of testing was made.

As shown previously, a large portion of the gross deflection of a pavement system occurs in the subgrade. Gross deflection will be larger, and the percentage of gross deflection that occurs in the subgrade will also be larger, for surfacing structures on weak subgrades than for those on strong subgrades. The percentage of gross deflection that occurred in the subgrade of the overlay system was slightly higher than that for the conventional system, indicating

that the subgrade over the overlay system was slightly weaker than that of the conventional system. Thus, it is concluded that the hypothetical difference in gross deflection could have been caused by the difference in subgrade strengths.

Effect of a Buried Bituminous Layer on Surface Deflection

Although variations in subgrade conditions are the major contributors to differences in gross deflections, variations in the components of the surfacing structures also contribute to the difference. The most prominent difference in the structures under review is the old bituminous layer at the base of the overlay structure.

An overlay structure that is bounded on both sides by a relatively firm layer, such as an asphaltic concrete layer, is less flexible than one so bounded on one side only, as is a conventional structure. Thus, it may be deduced that an overlay structure would permit lower gross deflection than would a conventional structure. In the hypothetical situation under investigation, the difference in gross deflections was of a nature such that the lower

bituminous layer did not have the aforementioned effect.

Effect of Radial Distance on Layered System Response

FIGURES 4 and 5 show the average deflection bowl patterns for the conventional and overlay cross-sections, respectively. They indicate that the deflecting shape of the pavement structures approximated that for a flexible plate subjected to a point load.

FIGURE 4 indicates that the effect of the individual layers decreased rapidly as the radial distance from the center of the loaded area increased. Beyond a distance of approximately one foot, the measured deflection at any level within the structure was identical to that at the surface.

FIGURE 5 indicates a pattern for the overlay structure similar to that of the conventional structure, except that the radial distance to a coincident pattern for all levels within the overlay structure increased to approximately two feet.

Because the individual layers of a pavement structure possess different moduli of elasticity, they should exhibit individual deflection patterns beyond the loaded area. A comparison of FIGURES 4 and 5 indicates that the individual patterns extended only for a radial distance of one foot for the conventional structure and two feet for the overlay structure. Thus, it is concluded that the individual layers of the overlay system reacted independently over a larger area than did those of the conventional structure.

Absorption of Deflection by Layers

FIGURES 4 and 5 show that the assumption regarding the lack of absorption of deflections by the pavement structure, required for use of the Boussinesq equation, is incorrect and the individual layers do, in fact, absorb deflections.

The deflection absorption effect is a measure of the protective ability of a flexible pavement structure for a subgrade. Pavement structures without any deflection absorbing characteristics cause the deflection of the subgrade to be directly governed by the load applied to

the surface. The absorption of deflections by the pavement layers permits more of an applied load to be transferred to the pavement structure than to the subgrade. In other words, the flexing ability of the individual layers of a flexible pavement structure provides a safety factor for the subgrade strength.

Because mobilization of shear strength in the layers of a pavement system depends on deflection, it is essential that the layers absorb some of the deflection transmitted from the surface. The amount of absorption that any layer will take is dependent on the material comprising the layer and the thickness of the layer. The results from the AASHO (22) road test have shown that for the road test conditions, asphaltic concretes were more effective in reducing surface deflections than were granular base courses and sub-bases; that stabilized granular base courses were more effective than granular subbases, although the sub-base was subjected to a less vertical stress than the base course; and that a gravel base course was more effective than a crushed stone base course.

TABLES VII and VIII show the deflection-absorption characteristics of the pavement structures as single units. The tables indicate that there was not much difference between the absorption characteristics of the overlay system and the conventional system. Through a thickness of 18.3 inches, the conventional structure absorbed 0.0074 inches, or approximately 28 per cent, of the gross deflection. Through a thickness of 17.4 inches, the overlay structure absorbed 0.0063 inches, or approximately 23 per cent, of the gross deflection. This finding was shown previously on FIGURES 4 and 5 and indicates that neither structure, as a unit, was more superior than the other in absorbing deflections.

TABLES VII and VIII also show the absorption characteristics of the bituminous surfacing layers, the upper layers from the surface to the center of the base course, and the lower layers from the center of the base course to the subgrade.

TABLE VII

DEFLECTION ABSORPTION BY VARIOUS LAYERS, CONVENTIONAL STRUCTURE 39--3

Section	Surface to Base Course		Surface to Mid-Base		Mid-Base to Subgrade	
	$d\Delta$ (ins.x10 ⁻³)	T (inches)	$d\Delta$ ⁻³ (ins.x10 ⁻³)	T (inches)	$d\Delta$ (ins.x10 ⁻³)	T (inches)
21	1.7	5.4	3.5	10.8	4.1	5.4
22	2.2	5.1	6.4	12.5	2.2	7.3
23	1.7	5.1	3.5	11.9	1.9	6.7
24	1.5	5.7	4.0	12.2	3.4	6.4
25	3.4	5.1	6.1	11.4	2.8	6.3
26	0.9	4.8	3.3	12.0	3.1	7.2
Mean	1.9	5.2	4.5	11.8	2.9	6.6
Std. Dev- iation	0.8	0.3	1.3	0.6	0.7	0.6

$d\Delta$ = change in deflection
T = thickness of layer

TABLE VIII

DEFLECTION ABSORPTION BY VARIOUS LAYERS, OVERLAY STRUCTURE 39-5/6

Section	Surface to Base Course		Surface to Mid-Base		Mid-Base to Subgrade	
	$d\Delta$ (ins. $\times 10^{-3}$)	T (inches)	$d\Delta$ (ins. $\times 10^{-3}$)	T (inches)	$d\Delta$ (ins. $\times 10^{-3}$)	T (inches)
11	0.7	3.3	0.9	9.5	4.3	8.8
12	-2.9	3.0	2.6	10.5	4.7	10.3
13	1.2	3.3	2.3	9.3	3.7	8.5
14	2.9	3.3	3.6	8.8	2.0	8.2
15	2.4	2.5	3.1	8.0	3.5	7.8
16	1.0	3.5	4.0	8.5	3.8	7.8
17	3.3	3.5	4.6	9.0	1.2	8.0
18	0	3.3	3.7	8.8	2.8	8.0
19	1.0	3.3	3.3	8.8	2.4	8.2
20	6.3	3.3	-	-	3.1	8.2
Mean	1.6	3.2	3.1	9.0	3.2	8.4
Std. Dev- iation	2.5	0.3	1.1	0.6	1.1	0.7

$d\Delta$ = change in deflection
T - thickness of layer

Through a thickness of 5.2 inches, the surfacing layer of the conventional structure absorbed 0.0019 inches, or 7.3 per cent, of the gross deflection. Through a thickness of 3.2 inches, the surfacing layer of the overlay structure absorbed 0.0016 inches or 5.8 per cent, of the gross deflection. The amount of absorption per inch of thickness was 0.0036 inches for the conventional structure and 0.0050 inches for the overlay structure. It is thus concluded that the surfacing layer on the overlay structure was superior to that on the conventional structure in absorbing deflections.

Through a thickness of 11.8 inches, the upper layers of the conventional structure absorbed 0.0045 inches, or 20.1 per cent, of the gross deflection. Through a thickness of 9.0 inches, the upper layers of the overlay structure absorbed 0.0031 inches, or 11.1 per cent, of the gross deflection. The respective rates of absorption were 0.0038 and 0.0034 inches per inch. It is thus concluded that the upper layers of both structures were equivalent in absorbing deflections.

Through a thickness of 6.6 inches, the lower layers of the conventional structure absorbed 0.0029 inches, or 11.1 per cent, of the gross deflection. Through a thickness of 8.4 inches, the lower layers of the overlay structure absorbed 0.0032 inches, or 11.5 per cent, of the gross deflection. The respective rates of absorption were 0.0044 and 0.0038 inches per inch. It is thus concluded that the lower layers of both structures were equivalent in absorbing deflections.

The quantitative study of the absorptive qualities of the individual layers of both structures has confirmed the previous indication that neither structure was superior to the other in absorbing deflections. However, the study indicated that a bituminous surfacing layer was superior to granular layers and, because of this reason, it should be advantageous to have the lower bituminous layer in an overlay structure located such that this superior quality is used.

Summary

The study of deflections within the pavement structures indicated that neither structure permitted

a gross deflection that was significantly different from that of the other structure.

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The patterns of the deflection bowls were significantly different and will be discussed in a later chapter.

The individual layers of the overlay system exhibited individual deflection patterns over a larger area than did those of the conventional system.

The bituminous surfacing layer on both structures was the most effective single layer in absorbing deflections, but there was little difference in the absorption qualities of the structures as units.

CHAPTER V

MODULAR RATIOS OF LAYERED PAVEMENT SYSTEMS

General

Modular ratios of the layers of a pavement system are indicators of the stiffness or inflexibility of that system. They express relationships between the stress-strain characteristics of one layer to those of another and thus may be taken as indicators of relative strengths.

The modular ratio is the ratio between the modulus of elasticity of one layer and that of another layer, usually adjacent to the first layer. The modulus of elasticity is the ratio of the unit stress to the unit strain for any value of stress below the proportional elastic limit (1). For many materials, this modulus is constant over a wide range of stress applications; for others, the range is minute.

Soils do not exhibit a constant modulus over an appreciable range of stress and are not, therefore, truly elastic materials. The degree of elasticity is high under specific conditions but, generally, soils are relatively inelastic. Poisson's ratio, the ratio of the strain normal to the applied stress to that parallel to the applied stress, is generally assumed to be 0.5, indicating no volume change during deformation, but studies have shown that the value is closer to 0.35 (32).

The magnitude of the modulus of elasticity of a pavement layer is governed by the stiffness of that layer which, in turn, is dependent on the inter-particle relationship in the materials composing that layer. A well compacted soil is stiffer than a loose soil because interaction between particles is increased by compaction. Similarly, an aggregate that is held together with asphalt is stiffer than the aggregate alone. The modulus, therefore, is an indicator of the relative stiffness of a layer and stiffness is a qualitative indicator of the strength of that layer.

The reaction of a pavement system to an applied load is controlled by the stiffness of that system. Vertical and horizontal stresses and strains, deflections and radii of curvatures of deflection bowls, strengths, and overall performance of the system are all affected by stiffness.

Stiffness is controlled by many variables but, in a general sense, the main variables are the quality and thickness of the layers comprising that system. Of the layers forming a pavement system, the weakest is usually the subgrade and the quality of that layer contributes most to the system reactions. Of the layers forming a pavement structure, the bituminous surfacing layer is the major contributor to the success of that structure and the thickness of that layer contributes most to the structure reactions.

The modular ratio of a pavement system can be found by various procedures utilizing both dynamic and static loading system. However, to date most of the studies have involved plate bearing tests on individual layers either during construction or by destructive

means after construction.

Modular Ratio of Conventional Pavement System

TABLES IX and X show the moduli of elasticity as determined by the deflection bowl procedure (31) for each of the six sections of conventional system. These tables show that the average modulus for the pavement structure was 37,075 p.s.i. and that for the subgrade was 14,840 p.s.i., for an average modular ratio of 3.5 based on the deflection pattern shown in FIGURE 4.

There was little agreement between the ratios as determined at a radial distance equal to the thickness of the pavement structure, H , and that at a radial distance equal to twice the thickness. The respective modular ratios were 5.0 and 2.0, which led to respective pavement moduli of 38,000 p.s.i. and 36,150 p.s.i. and to respective subgrade moduli of 7,700 p.s.i. and 21,980 p.s.i. The reasons for this variation may be that the small deflections at a radial distance of $2H$ fell outside the accuracy of the Benkelman beam procedure or that the loading arrangement did not meet the requirements of the

TABLE IX

MODULUS OF ELASTICITY AT RADIAL DISTANCE = H: CONVENTIONAL SYSTEM 39-3

Section	H (ins.)	Δ_o^{-3} (ins.x10 ⁻³)	Δ_H^{-3} (ins. x10 ⁻³)	$\frac{\Delta_o}{\Delta_H}$	$\frac{E}{E_s}$	$\frac{E_p}{E_s}$ (psi)	$\frac{E_s}{E_p}$ (psi)
21	16.2	25.1	10.4	2.41	5	47900	9580
22	19.8	22.7	7.9	2.88	5	40100	8020
23	18.6	23.5	8.9	2.64	5	40900	8180
24	18.6	28.8	9.8	2.94	4	33300	8330
25	17.7	30.1	12.0	2.51	5	33500	6700
26	19.2	26.7	10.5	2.54	6	32400	5400
Mean	18.4	26.1	9.9	2.65	5	38000	7700
Std. Dev- iation	1.2	2.7	1.3	0.60	0.5	5500	1330

TABLE X

MODULUS OF ELASTICITY AT RADIAL DISTANCE - 2H: CONVENTIONAL SYSTEM 39-3

Section	H (ins.)	Δ_o (ins.x10 ⁻³)	Δ_{2H} (ins.x10 ⁻³)	$\frac{\Delta_o}{\Delta_{2H}}$	$\frac{E_p}{E_s}$	E _p (psi)	E _s (psi)
21	16.2	25.1	4.6	5.46	3	40200	13400
22	19.8	22.7	3.1	7.32	1	40100	40100
23	18.6	23.5	3.5	6.71	2	38900	19500
24	18.6	28.8	4.0	7.20	1	31600	31600
25	17.7	30.1	4.4	6.85	2	31900	15900
26	19.2	26.7	4.2	6.35	3	34200	11400
Mean	18.2	26.1	4.0	6.65	2	36150	21980
Std. Dev- iation	1.2	2.7	0.5	0.62	0.8	3700	8030

analytical procedure. Such reasons have been noticed as part of other investigations (31) and are inherent disadvantages in the method.

Burmister (4) has commented that modulus values of 5,000 p.s.i. to 10,000 p.s.i. represent "good" base course plus bituminous surfacing layers. The corresponding modular ratios for a "good" two-layer system would then range from 8 to 22. Comparatively, the conventional structure under test had a low modular ratio, with the modulus for the subgrade being relatively high and that for the pavement structure relatively low. Because the modulus for the pavement structure is a combination of that for the granular layers and that for the bituminous surfacing layer, the low value indicates that the granular layers are relatively weak.

The low modular ratio for this system indicates that protection is being provided to the subgrade largely by the thickness of pavement structure rather than by flexing action of the individual layers. As the ratio approaches unity, indicating that the elastic properties

of the subgrade are approaching those of the pavement structure, the assumption regarding homogeneity required for EQUATION 1 becomes applicable to the system. At this stage, the stresses at any point within the system are assumed to be controlled by the geometrics to that point rather than by material properties.

Modular Ratio of Overlay Pavement System

Because of the presence of the bituminous layer in the lower level of the overlay structure, it was anticipated that the stiffness of this system would be greater than that for the conventional system. The modulus of this layer, being relatively higher than either the subgrade beneath it or the granular layers above it, would tend to increase the moduli of the adjacent layers. Secondary effects should be that it would provide a firm base for compaction of the overlying granular layers, thereby permitting higher densities or increased stiffness to be placed in those layers, and it would 'sandwich' the granular layers between it and the upper mat, thereby imparting further stiffness to the granular layers.

TABLES XI and XII show the moduli of elasticity as determined by the deflection bowl procedure (31) for each of the ten sections of overlay system. These tables show that the average modulus for the pavement structure was 58,990 p.s.i. and that for the subgrade was 6,750 p.s.i., for an average modular ratio of 9.5 based on the deflection pattern shown in FIGURE 5.

As with the conventional structure, there was little agreement between the ratios as determined at a radial distance of H and those at a distance of $2H$. The respective modular ratios were 12.0 and 7.0, which led to respective pavement moduli of 73,200 p.s.i. and 44,780 p.s.i. and to respective subgrade moduli of 5,940 p.s.i. and 7,560 p.s.i. The causes for this variation are the same as those for the conventional structure.

A comparison of the average values for the overlay structure with those for the conventional structure indicates that the overlay pavement structure with a modulus of 58,990 p.s.i. is considerably more stiff than the conventional structure with a modulus of 33,075 p.s.i. The difference in pavement moduli, although of considerable magnitude, is

TABLE XI

MODULUS OF ELASTICITY AT RADIAL DISTANCE = H: OVERLAY SYSTEM 39-5/6

Section	H (ins.)	Δ_o (ins.x10 ⁻³)	Δ_H (ins.x10 ⁻³)	$\frac{\Delta_o}{\Delta_H}$	$\frac{E_p}{E_s}$	E _p (psi)	E _s (psi)
11	18.3	28.6	14.4	1.99	11	58800	5350
12	20.8	32.0	14.0	2.28	10	42000	4200
13	17.8	19.9	12.9	1.54	24	144800	6030
14	17.0	24.0	15.0	1.60	19	108500	5710
15	15.8	23.0	13.2	1.74	11	83500	7590
16	16.3	25.7	14.3	1.80	10	67300	6730
17	17.0	25.2	13.8	1.83	12	74300	6190
18	16.8	28.9	15.0	1.93	9	59800	6650
19	17.0	29.0	14.5	2.00	9	59600	6620
20	17.0	41.9	18.7	2.24	8	34400	4300
Mean	17.4	27.8	14.6	1.90	12	73200	5940
Std. Dev- iation	1.3	5.8	1.5	0.22	1.5	31000	1030

TABLE XII

MODULUS OF ELASTICITY AT RADIAL DISTANCE = 2H: OVERLAY SYSTEM 39-5/6

Section	H (ins.)	$\Delta \sigma$ (ins.x10 ⁻³)	Δ_{2H} (ins.x10 ⁻³)	$\frac{\Delta \sigma}{\Delta_{2H}}$	$\frac{E_p}{E_s}$	E _p (psi)	E _s (psi)
11	18.3	28.6	8.2	3.49	7	31900	4550
12	20.8	32.0	7.0	4.57	5	22500	4500
13	17.8	19.9	7.9	2.52	12	74700	6230
14	17.0	24.0	9.3	2.58	11	64700	5890
15	15.8	23.0	7.8	2.95	7	62700	8950
16	16.3	25.7	8.4	3.06	7	54300	7750
17	17.0	25.2	7.9	3.19	7	47600	6800
18	16.8	28.9	6.7	4.31	4	33200	8300
19	17.0	29.0	6.0	4.84	3	33200	11080
20	17.0	41.9	6.4	6.55	2	23000	11500
Mean	17.4	27.8	7.6	3.81	7	44780	7560
Std. Dev- iation	1.3	5.8	1.0	1.20	3.1	17700	2320

conservative because of the difference in subgrade moduli. The relatively high pavement modulus for the overlay structure is related to a relatively low subgrade modulus whereas the relatively low pavement modulus for the conventional structure is related to a relatively high subgrade modulus. If the subgrade moduli had been equal, there is little doubt that the difference in pavement moduli would have been considerably more in favour of the overlay structure.

The anticipation that the buried bituminous layer in the overlay structure would increase the stiffness of the pavement structure was realized and it is thus concluded that the overlay structure was considerably more stiff, and, therefore, considerably more protective to the subgrade, than was the conventional structure.

Granular Equivalency of Lower Bituminous Layer

A possible method of determining the effect of an underlying bituminous layer is to compare the thickness of the layer to the thickness of granular material required to support the same loading. If it is assumed that the total thickness, as measured in 'inches of gravel', of the conventional structure is sufficient to safely carry an applied

load, then the required total thickness, also measured in inches of gravel, of an overlay structure over the same subgrade should be identical.

Such a comparison was made, assuming:

- that the loading conditions on both structures were identical,
- that the gross deflection was 0.0300 inches for both structures.
- that the granular equivalency of the bituminous surfacing layer on both structures was four inches of granular material to one inch of bituminous mat, considered reasonable in view of the findings of the AASHO (22) road test,
- that the moduli of elasticity of the pavement structures were as determined by the deflection bowl procedure (31) at a radial distance of H,
- and that the moduli of elasticity of the subgrade were identical and equal to that determined by the deflection bowl procedure (31) at a radial distance of H for the conventional system.

(Sample calculations for the granular equivalency determination are contained in APPENDIX C.)

The lower bituminous layer, at a depth of approximately 15 inches below the surface, was equivalent to 5.0 inches of granular material per inch of bituminous mat. The conventional structure provided a protective cover equivalent to 34.0 inches of granular material whereas the overlay structure provided a protective cover equivalent to 37.4 inches of granular material. In other words, if the lower bituminous layer was equated to only granular subbase during the thickness design phase of this hypothetical overlay structure, an excess of 3.4 inches in thickness of granular material would have been placed.

Because of the assumptions used in this equivalency analysis, the quantitative results are questionable. However, the analysis indicates that the lower bituminous layer in an overlay structure is equivalent to more than unity with granular material and, from this indication, it is concluded that the layer should be treated so in thickness designs.

Deflection Equivalencies of Pavement Systems

A possible method of comparing the protective ability of pavement structures is to compare the gross deflections with the structures on the same subgrade. If the structures are of similar total thickness, the one with the lower gross deflection is more protective to the subgrade.

Such a comparison was made, assuming:

- that the loading conditions on both structures were identical,
- that the moduli of elasticity of the pavement structures were as determined by the deflection bowl procedure (31) at a radial distance of H,
- and that the moduli of elasticity of the subgrades were identical and equal to that determined by the deflection bowl procedure (31) at a radial distance of H for the conventional system.

(Sample calculations for the deflection equivalency determination are contained in APPENDIX C.)

By this analysis, the gross deflection of the conventional system is 0.0328 inches and that for the overlay system is 0.0184 inches, for a difference of 0.0144 inches in favour of the overlay system.

In Chapter IV, from a difference in measured gross deflection of 0.0017 inches in favour of the conventional system was not regarded as statistically significant, but it was concluded, for a hypothetical situation, differences in subgrade strengths would be a major contributor to differences in gross deflections. The analysis of deflection equivalencies indicates that, with subgrade conditions being equal, the superiority of the overlay structure is more pronounced. It is now concluded that, with subgrade conditions being equal, an overlay structure should be more effective in controlling deflections than a conventional structure because of the lower bituminous layer in the overlay structure.

Summary

The study of the moduli of elasticity of the pavement systems indicated that the overlay structure is stiffer than the conventional structure. The cause of this difference is attributed to the presence of the lower bituminous layer in the overlay structure. The value of this layer is several times that of granular material and should be so evaluated during the design of overlay structures.

CHAPTER VI

DEFLECTION PATTERNS WITHIN LAYERED PAVEMENT SYSTEMS

General

It was stated previously that a pavement structure develops shear strength by means of deflections that are in accordance with the theory of elasticity. If a pavement layer is assumed to react to an applied load in a manner similar to that of a flexible plate, the deflection pattern around the loaded area will be bowl-shaped. The radius of curvature of the bowl is dependent on the intensity of the load and on the thickness and the relative stiffness of the layer.

The radius of curvature is an indicator of the flexibility of, and the flexural stresses developed in, a layer. The radius is controlled by the stiffness of the upper layers of a structure whereas deflection is controlled by the stiffness of all layers (23). For a

given radius of curvature, the stresses developed in a layer increase as the thickness or the stiffness of the layer increases (23). The radius is also an indicator as to where in the system the major portion of the deflection is occurring. Walker et al (25) have shown that the radius of curvature of the deflection bowl is small if the major portion of the gross deflection is occurring in the upper layers; if the radius is large, most of the deflection is occurring in the subgrade.

The criterion used for judgement of the performance of a pavement structure is that the structure withstand the loads imposed upon it. Some pavements do exhibit distress in the form of 'alligator' cracking, an indication that excessive stresses and strains exist in the upper layers of the pavement structure. It has been shown that such cracking is not directly related to subgrade soil conditions, pavement structure thickness, or pavement deflection but to radius of curvature of the surface deflection bowl (23), (25). To prevent such distress, a pavement structure should react to imposed loads such that the bowl has a long radius of curvature.

Because an overlay system has characteristics of stiffness which are superior to those of a conventional system of equivalent geometrics, the radii of curvature of the layers of such a system should be longer than those of a conventional system. Dehlen (23) found that a radius of curvature less than 125 feet, at a maximum deflection of 0.055 inches, was associated with 'chicken-wire' cracking. Although these values are applicable only to the structures for which they were determined, they may serve as comparative values for other structures.

Radius of Curvature of Surface Deflection Bowls

A deflection bowl measured on the surface represents the deflecting reactions of the entire pavement system, including the subgrade. For a fixed intensity of loading, a weak system will show a short radius surface bowl and a strong system will show a long radius.

FIGURE 7 shows that the average surface deflection patterns for the systems under study followed the general bowl-shape of a flexible plate. The radius of curvature for the surface bowl was 566 feet for the

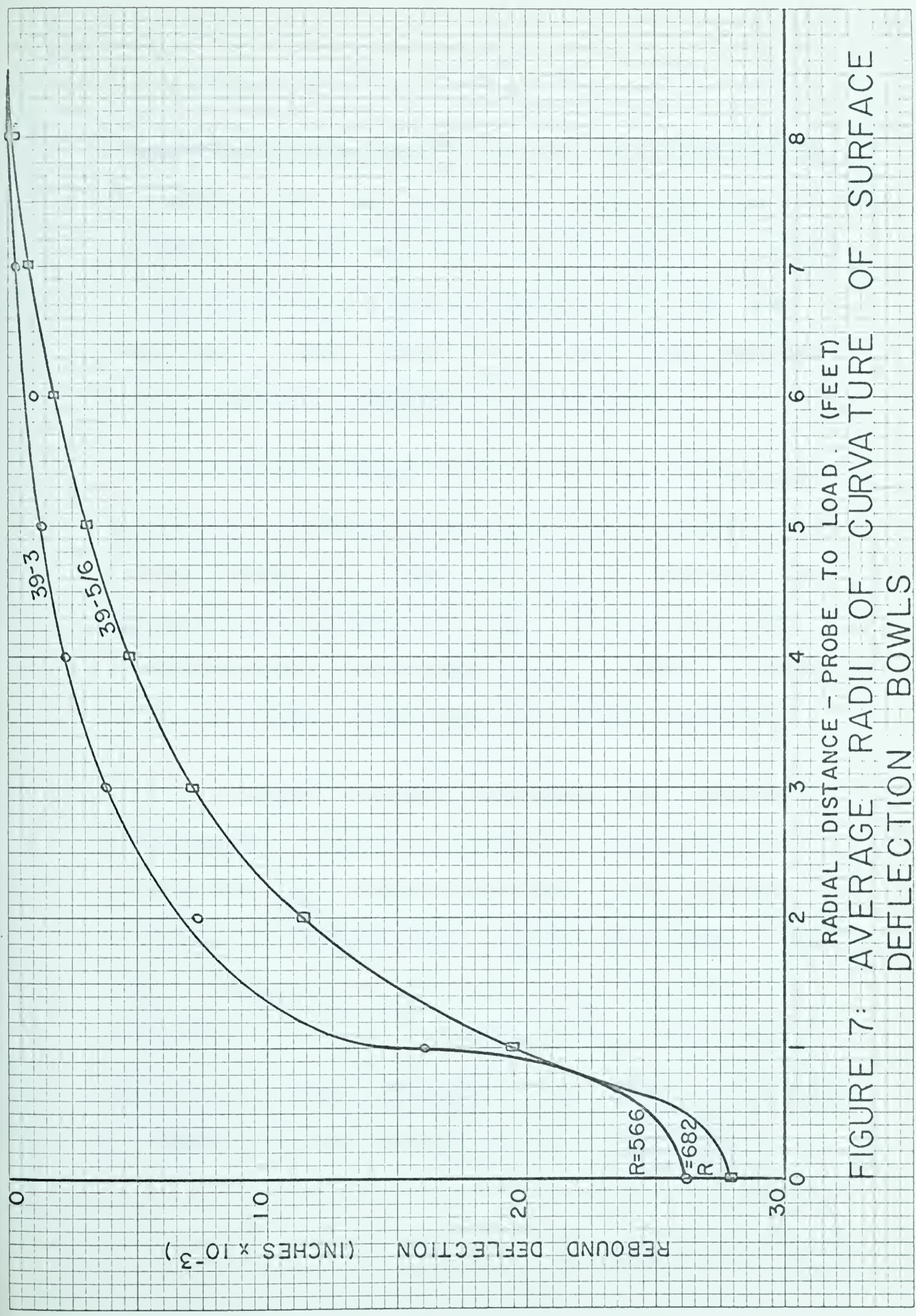


FIGURE 7: AVERAGE RADII OF CURVATURE OF SURFACE DEFLECTION BOWLS

conventional system and 682 feet for the overlay system. (Throughout this chapter, numerical values have been calculated for the radii of curvature. However, because of the approximate nature of the plotted curves, the magnitudes of these values have not been given emphasis but are used for comparative purposes only.)

These findings indicate that the conventional system had a sharper bowl than the overlay system and, because flexing of a layer causes tensile stresses and strains to occur within the layer, also indicate that the conventional system permitted more tensile effects in the individual layers than did the overlay system.

Because a surface deflection bowl represents the flexing of the entire system, it is not practical to use such bowls to determine where in the pavement structure the maximum tensile effects took place. However, a comparison of the radii of curvature under the loaded area at various interfaces within the structures will permit a closer inspection of the effect of the layers in reducing and distributing stresses and strains.

Radius of Curvature of Upper Layer Deflection Bowls

Because the effect of a load applied to the surface decreases as depth to the interface of measurement increases, it was anticipated that the radius of curvature of the deflection bowls would increase with depth. FIGURE 8 shows the deflection bowl patterns for the interior interfaces of the pavement structures and indicates that the radius did increase with depth.

FIGURE 8 shows the patterns for the interface between the upper bituminous surfacing layer and the granular base course. If it is assumed that there is continuous contact between the layers, these patterns are identical to those for the bottom of the bituminous layer.

Comparison of FIGURE 7 with FIGURE 8 indicates that the radius of curvature of the conventional structure increased from 566 feet at the surface to 690 feet at the base course, a 22 per cent increase through 5.2 inches of asphaltic concrete. The corresponding increase for the overlay structure was from 682 feet to 834 feet, a 22 per

THE HISTORY OF THE UNITED STATES

The history of the United States is a story of growth and change. From the first settlers to the present day, the nation has evolved through various stages of development. The early years were marked by exploration and settlement, followed by a period of rapid expansion and industrialization. The American Revolution was a pivotal moment in the nation's history, leading to the establishment of a new government and the declaration of independence. The 19th century was a time of great achievement, with the nation expanding its territory and developing its economy. The Civil War was a defining moment in the nation's history, leading to the abolition of slavery and the strengthening of the Union. The 20th century has been a time of great change, with the nation becoming a world power and facing new challenges. The American people have shown a remarkable ability to adapt and overcome, and the United States continues to be a land of opportunity and hope.

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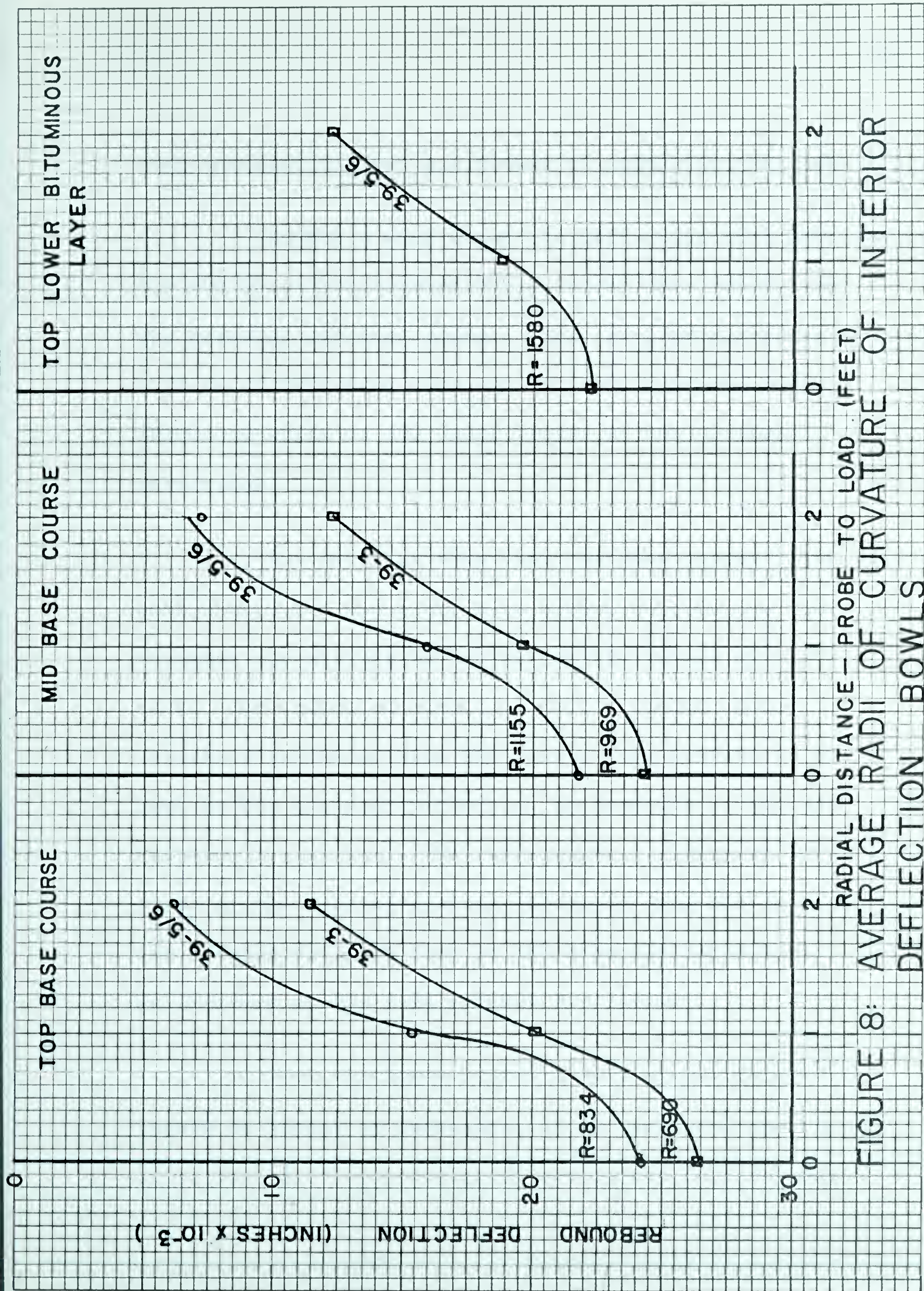


FIGURE 8: AVERAGE RADII OF CURVATURE OF INTERIOR DEFLECTION BOWLS

cent increase through 3.2 inches of asphaltic concrete.

FIGURE 8 also shows the deflection bowl patterns for the interface between the granular base course and the granular sub-base course. The radii of curvature at this level have been taken as indicative of the flexure characteristics of the upper layers of the pavement structures.

The patterns show that the base course layer of both structures had a definite effect on reducing the stresses and strains by increasing the radius of curvature. The radius of curvature of the conventional structure increased from 566 feet at the surface to 969 feet at the granular interface, an increase of 403 feet through 11.8 inches. The corresponding radius of curvature of the overlay section increased from 682 feet at the surface to 1,155 feet at the granular interface, an increase of 473 feet through 9.0 inches.

From the study of the effect of the upper layers on radius of curvature, it is concluded that the upper layers of the overlay structure are considerably

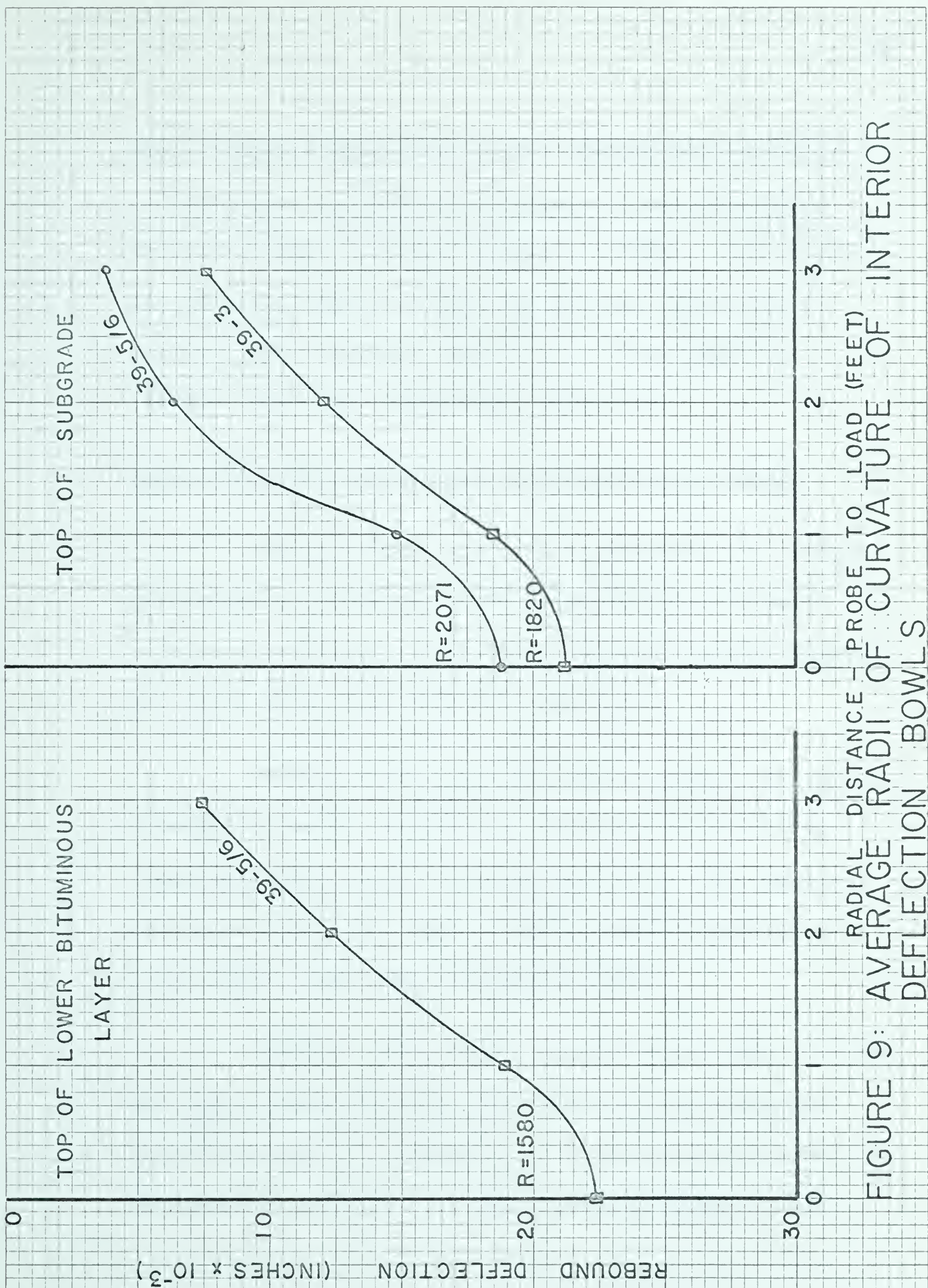


FIGURE 9: AVERAGE RADII OF CURVATURE OF INTERIOR DEFLECTION BOWLS

more effective than those of the conventional structure in increasing the radius of curvature, and decreasing tensile effects, with an increase in depth. The reason for this difference is that the overlay structure is stiffer, and therefore subject to a lower degree of flexure, than the conventional structure.

Radius of Curvature of Lower Layer Deflection Bowls

The preceding discussion indicated that radius of curvature increases as the depth within a pavement structure increases. This effect should continue through the lower layers and into the subgrade.

FIGURE 9 shows the deflection pattern for the interface between the granular sub-base and the lower bituminous layer of the overlay structure. The radius increased from 1,155 feet at the granular interface to 1,580 feet at the lower bituminous layer.

FIGURE 9 also shows the deflection bowl patterns for the interface between the bottom of the surfacing structures and the subgrades. The differences between the radii of curvature at this level and those at the

aforementioned granular interface have been taken as indicative of the flexure characteristics of the lower layers of the pavement structures.

The radius of curvature of the conventional structure increased from 969 feet at the granular interface to 1,820 feet at the subgrade, an increase of 851 feet through 6.6 inches, whereas that of the overlay structure increased from 1,155 feet at the granular interface to 2,071 feet at the subgrade, an increase of 916 feet through 8.4 inches. From this finding, it is concluded that the lower layers of the overlay structure are less effective than those of the conventional structure in increasing the radius of curvature with an increase in depth.

FIGURE 9 also shows directly the worth of a lower bituminous layer in an overlay structure in reducing tensile effects on a subgrade. In the overlay structure under investigation, the radius increased 491 feet through a bituminous layer thickness of 2.6 inches whereas the radius increased only 851 feet through a granular subbase thickness of 6.6 inches in the

conventional structure. With this finding as a basis, it is concluded that, from a consideration of radius of curvature increase and tensile effect decrease on the subgrade, a bituminous layer at depth is considerably more effective than granular subbase.

Summary

The study of radii of curvature of the pavement systems indicated that the individual layers of the overlay system are more effective in increasing radius with depth than those of the conventional system.

The combined effect, as shown by the radius of curvature of the surface deflection bowl, indicated that the conventional system is more flexible, or less stiff, than the overlay system.

FIGURES 10 and 11 summarize the deflection patterns of the systems under investigation.

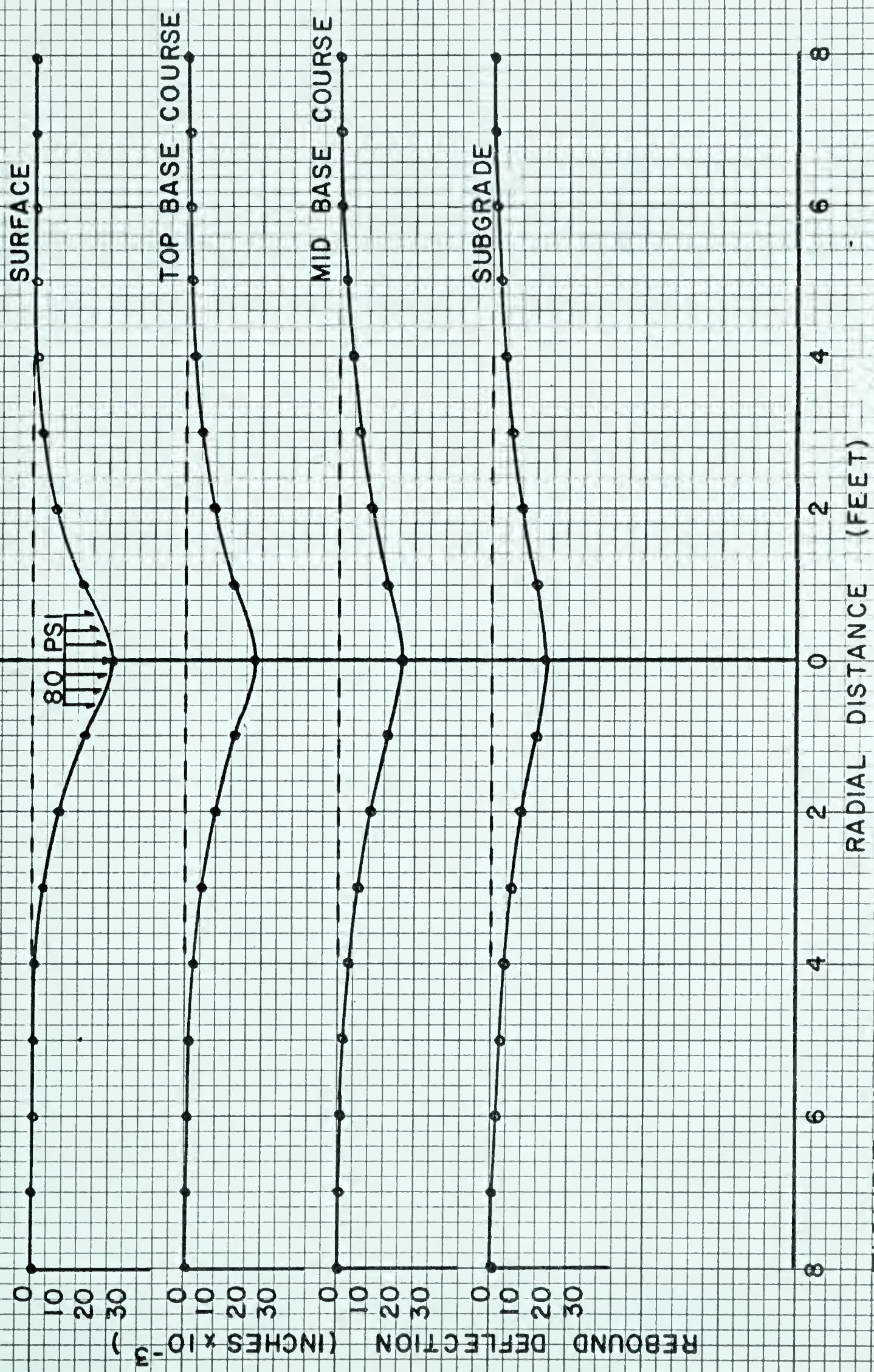


FIGURE 10: DEFLECTION PATTERNS OF CONVENTIONAL SYSTEM 39-3

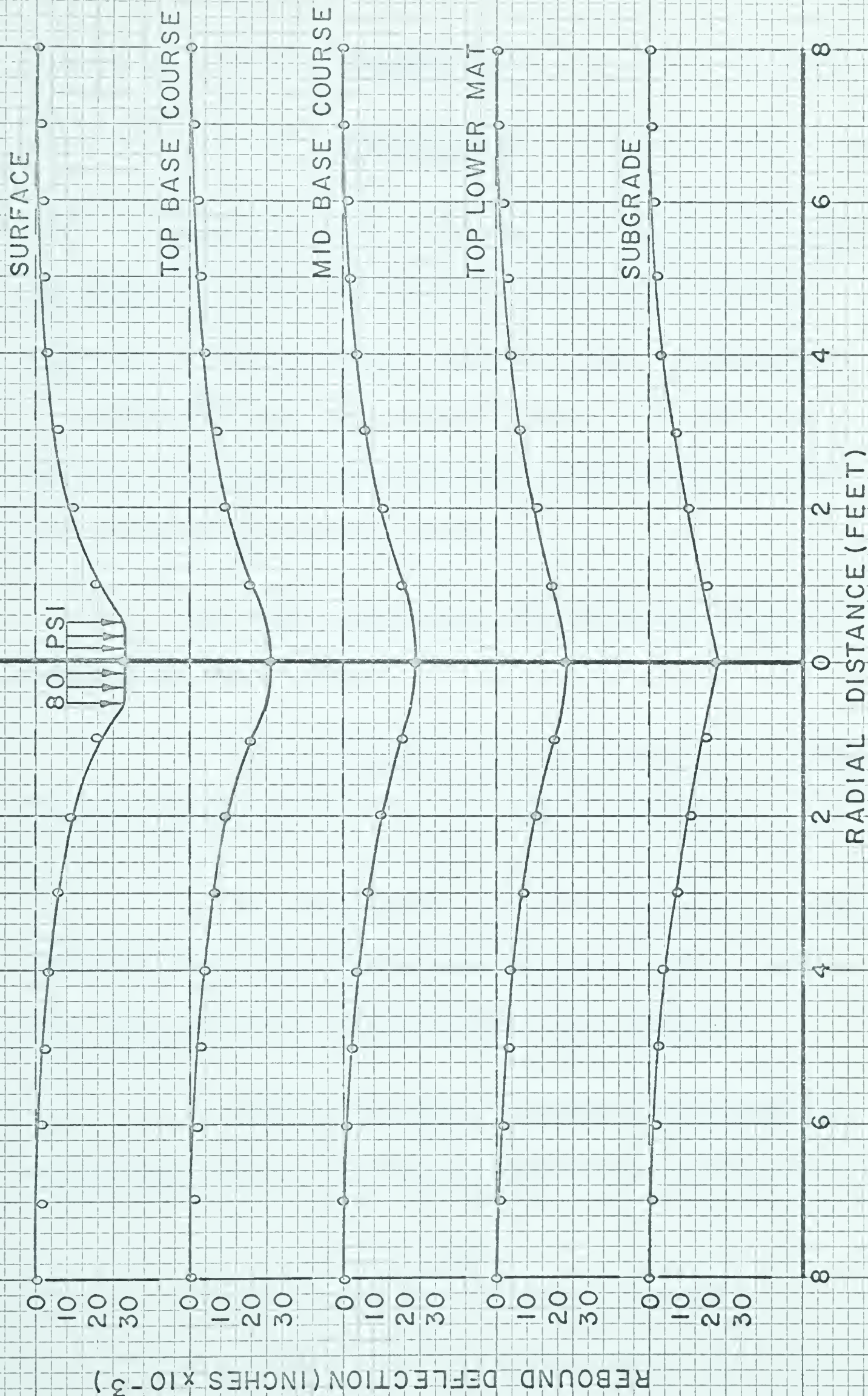


FIGURE 11: DEFLECTION PATTERNS OF OVERLAY SYSTEM

39-5/6

CHAPTER VII

CONCLUSIONS

The aim of this investigation was to evaluate the worth of a lower bituminous layer of an overlay structure. The evaluation was made from a comparison of maximum deflections, modular ratios, and radii of curvature of deflection bowls of a conventional system with those of an overlay system.

From this comparison, the following specific conclusions were formed:

1. The difference in gross deflection between the two systems was not statistically significant.
2. The individual layers of the overlay system exhibited individual deflection patterns over a larger area than did those of the conventional system.
3. From an analysis of moduli of elasticity and modular ratio, the overlay system was stiffer than the

conventional system.

4. From analytical reasoning with hypothetical subgrades of equal modulus of elasticity, the overlay system was superior to the conventional system in controlling deflections.

5. For systems with equal gross deflection and with subgrades of equal modulus of elasticity, the gravel equivalency of the lower bituminous layer in an overlay system is greater than unity with granular subbase at an equivalent depth in a conventional system.

6. The individual layers of the overlay system were superior to those of the conventional system in increasing radius of curvature of deflection bowls with depth.

7. The surfacing structure of the conventional system was more flexible, as determined from radius of curvature of the surface deflection bowl, than that of the overlay system.

The general conclusion of this investigation is that the lower bituminous layer in an overlay system causes that system to become stiffer, and therefore less affected by deflections, than does granular subbase at an equal depth cause a conventional system. On the basis of this investigation, it is recommended that the lower bituminous layer be assigned a gravel equivalency greater than unity in the design of overlay pavement structures.

CHAPTER VIII

RECOMMENDATIONS FOR FURTHER RESEARCH

This investigation was conducted to establish qualitative trends of the worth of a lower bituminous layer in an overlay structure. The trends have been shown but further research is required to substantiate or refute them. Suggested research programs are:

1. Repetition of this investigation to determine if the trends apply in general or are limited to the structures tested.
2. Repetition of this investigation under spring conditions, at the time of maximum deflections, to determine if the trends are applicable to maximum conditions.
3. Measurement of deflections and radii of curvature of the various layers on the layer surfaces during construction or by destructive procedures on abandoned highways.

4. Installation of minute pressure cells to measure pressures at various interfaces to substantiate deflection measurements.

5. Use of non-destructive vibratory procedures to evaluate modular ratios of in-service pavement systems of various types.

6. Construction of overlay test sections in which the depth to the lower bituminous layer is varied in order to subject the conclusions of this investigation to a rigorous examination.

The need for resurfacing flexible pavements by overlay construction is becoming more urgent. Knowledge of the reactions of an overlay structure to imposed loads is rather meagre at this time. This investigation has provided a small amount of such vital knowledge; more is required.

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APPENDIX A

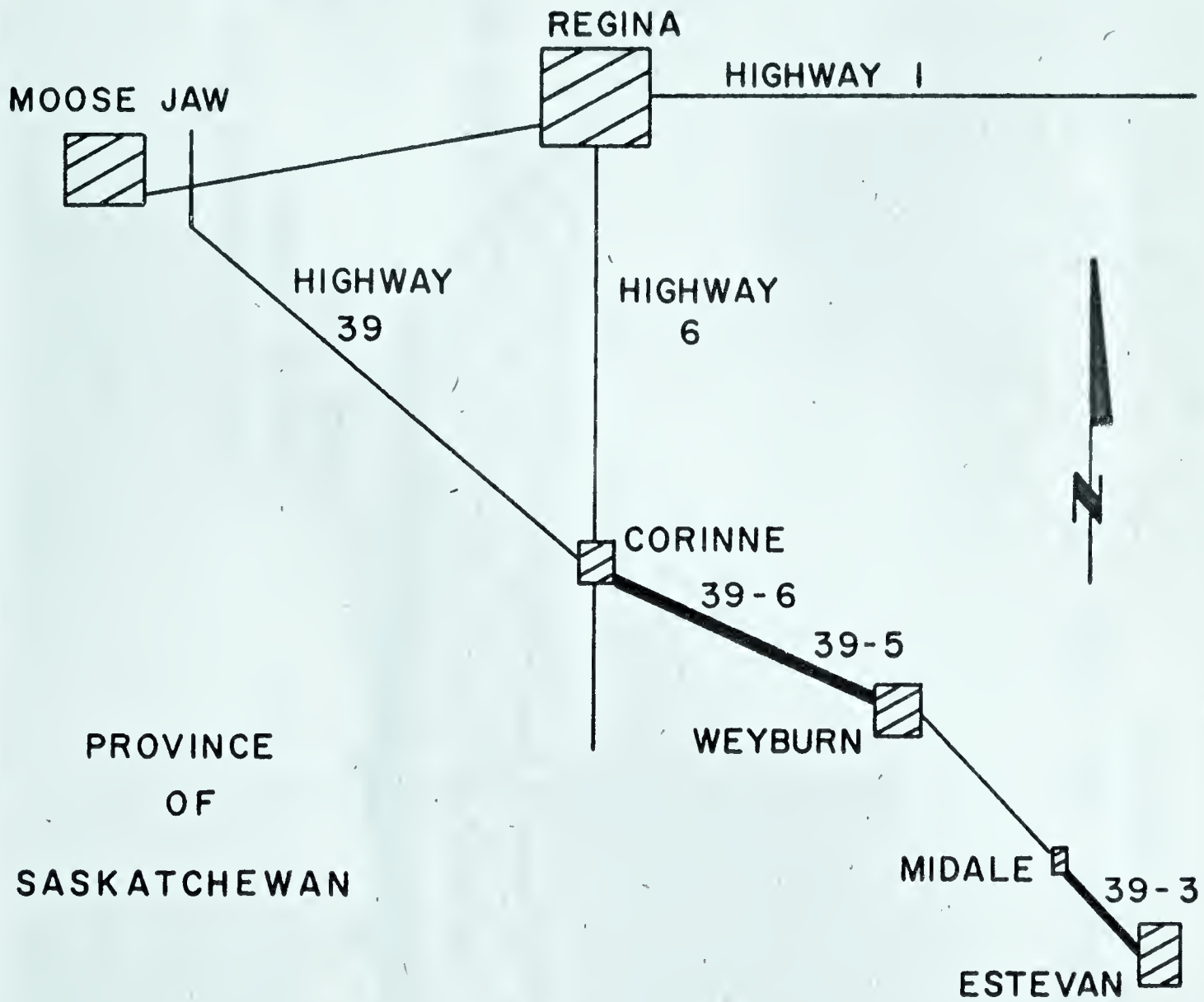


FIGURE A-1: LOCATIONS OF TEST SECTIONS

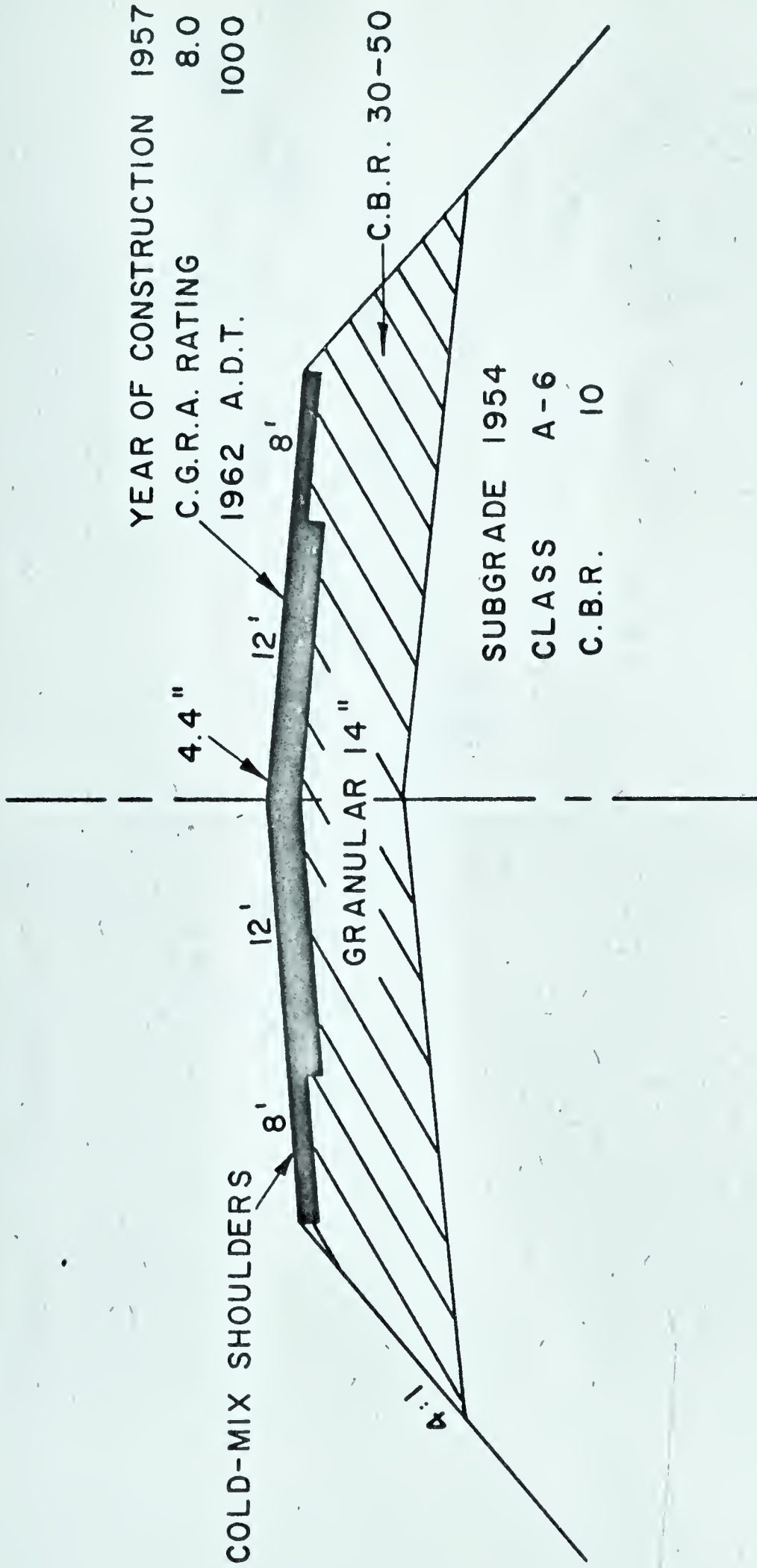


FIGURE A-2: TYPICAL CROSS-SECTION, CONVENTIONAL SYSTEM

39-3

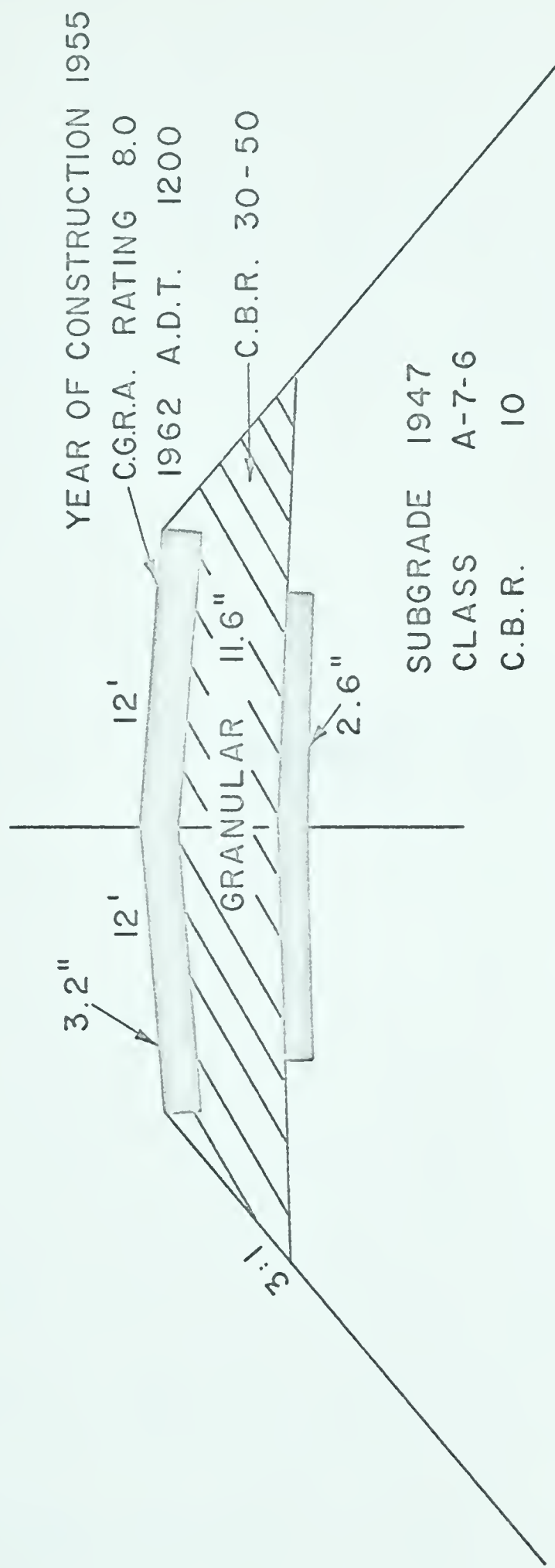


FIGURE A-3: TYPICAL CROSS - SECTION, OVERLAY SYSTEM
39-5/6

APPENDIX B

MODIFIED CGRA DEFLECTION TEST PROCEDURE

Scope

This method covers a procedure for the determination of the static rebound deflection of a pavement under a standardized axle load, tire, size, tire spacing, and tire pressure.

Equipment

The equipment included:

- 1) A.U.S. Bureau of Public Roads type Benkelman beam
(see FIGURE B-1 for construction details).
- 2) A 5-ton truck having an 18,000 pound rear axle load equally distributed on two wheels, each equipped with dual tires. The tires were 10.00 x 20, 12-ply, inflated to a pressure of 80 p.s.i.
- 3) Tire pressure measuring gauge.
- 4) Thermometer (0°-120°F.) with 1° divisions.
- 5) A mandrel for making a 1.75 inch deep hole in the pavement for temperature measurement. The diameter of the hole at the surface was one-half inch and at the bottom three-eighths of an inch.

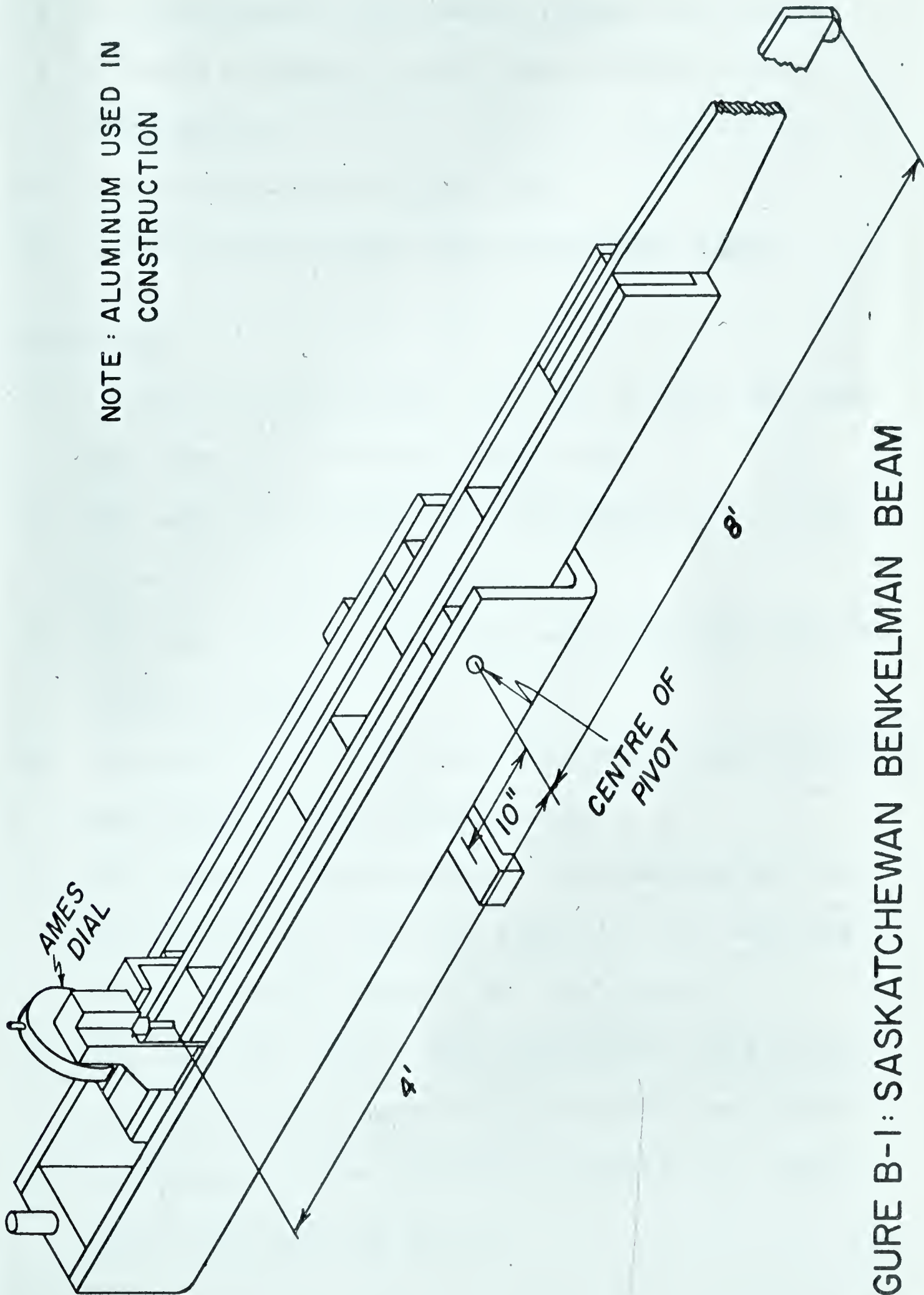


FIGURE B-1: SASKATCHEWAN BENKELMAN BEAM

- 6) A three-quarter inch diamond-tipped core barrel.
- 7) A series of special probes (see FIGURE B-2 and description).
- 8) A portable electric drill rig.
- 9) A 6-inch core barrel and a 4-inch hand auger.

Procedure

- 1) A point on the pavement, 3.0 feet in from the pavement edge, was selected and marked.
- 2) The layer thicknesses were determined from 6-inch cores and 4-inch hand augers.
- 3) The dual wheels of the truck were centered over the selected point.
- 4) The probe of the beam was inserted between the wheels and placed on the selected point.
- 5) The locking pin was removed from the beam and the legs adjusted so that the plunger of the beam was in contact with the stem of the dial gauge.
- 6) The gauge was set at approximately 0.4 of an inch and the initial reading recorded when the rate of deformation of the pavement was equal to or less than 0.001 inch per minute.

- 7) The truck was moved forward at 1 foot increments and dial readings recorded at each increment. At a distance of 8 feet, the truck was stopped. This step was repeated 5 times.
- 8) A three-quarter inch core was removed from the surface bituminous layer and a special probe and casing was inserted into the hole to rest on the base course.
- 9) The deflection measuring procedure was repeated.
- 10) The probe and casing were removed, the three-quarter inch hole was extended to the mid-base course interface, the probe and casing were re-inserted and the deflection measuring procedure was repeated.
- 11) In a similar manner, deflection measurements were taken at the top of the lower bituminous mats in overlay sections and at the top of all subgrades.
- 12) Pavement and air temperatures were recorded at least once every hour, inserting the thermometer in the standard hole and filling up the hole with water.
- 13) The tire pressure was checked at regular intervals and adjusted when necessary.
- 14) The entire procedure was repeated at a second selected point located approximately 10 feet behind the

first point.

- 15) The deflections at each radial distance for each interface from the two points were averaged and the average was assumed to be applicable for the highway section under test.

SUBSURFACE DEFLECTION PROBE

A special probe for the subsurface deflection measurements was developed for this research work. With this probe and the Benkelman beam, deflections at any point within a pavement system could be measured with only a minute amount of destruction to the structure.

The design of the probe was based on three controls: (1) it had to be free to move vertically in the order of one-thousandths of an inch; (2) it had to be free from the effects of the surrounding medium; and (3) it had to have a base measurement such that it would approximate a point, yet would not cause minute shear failure, or "punch" into the supporting medium. FIGURE B-2 shows the final production probe.

The casing prevented the granular soils from slumping into the bore hole and provided lateral support for the probe. It was machined to fit snugly into the bore hole, yet with a minimum of disturbance to the surrounding medium. The probe was machined to fit loosely,

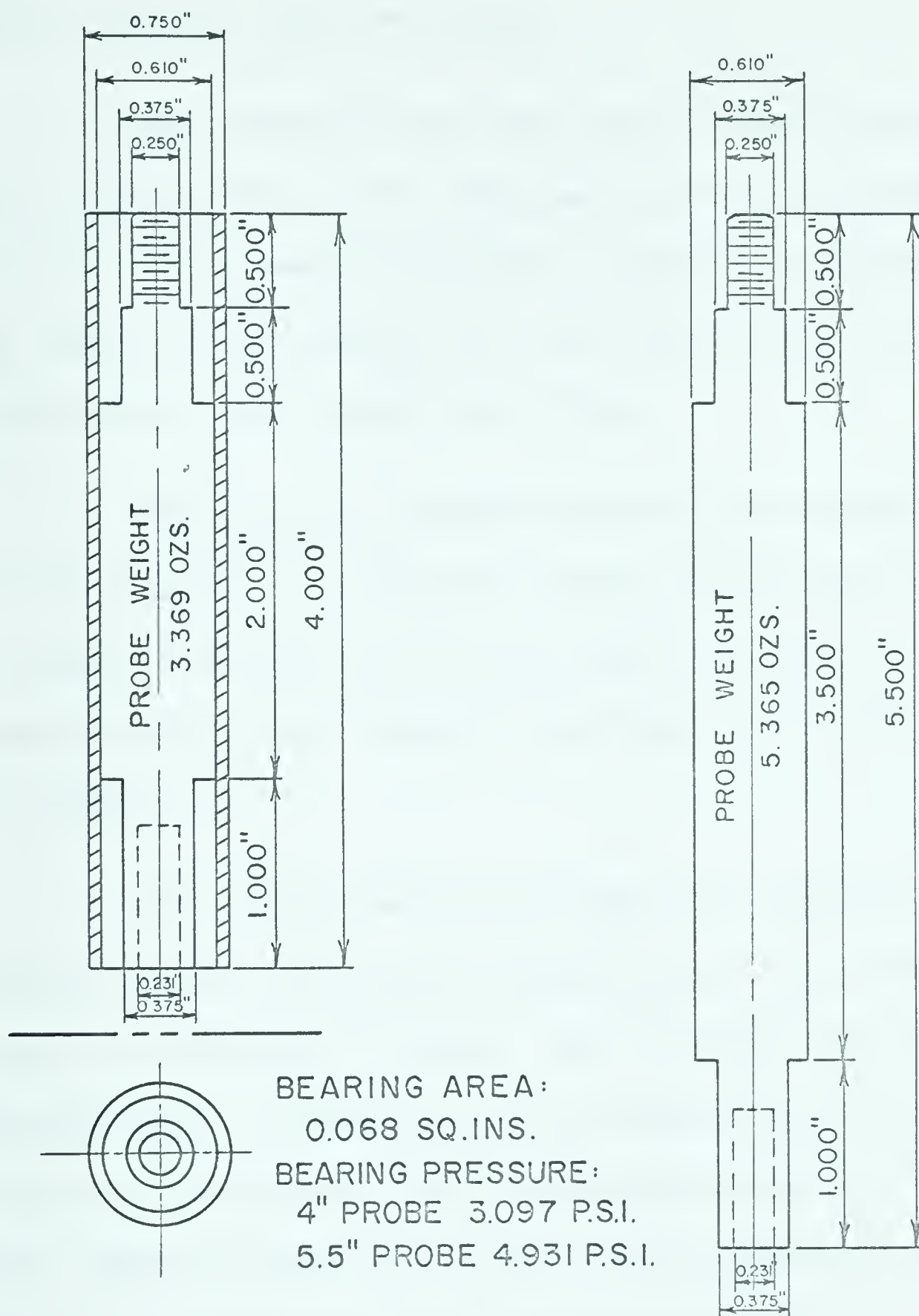


FIGURE B-2 : SPECIAL STEEL PROBE FOR DEFLECTION MEASUREMENTS WITHIN A PAVEMENT STRUCTURE

without wobble, into the casing.

The weight of the probe and a film of lubricating oil on the outside of the probe ensured that the probe would move the minute amounts required. Repeated measurements on the casing and the probe led to the conclusion that the probe moved freely inside the casing.

The probe was manufactured in two lengths, a 5½-inch length and a four-inch length. With these lengths, a combined probe of any desired length could be had. The couplings were screw-fitted to eliminate "free play" at the joints.

The tapped end of the probe also served as the bearing end and the annular-shaped bearing area, small enough to approximate a point, did not punch into the granular soil. Although it was anticipated that the weight of a long probe would cause punching into a loose sand, repeated tests on the base course mixtures involved failed to substantiate this anticipation.

The probe-casing arrangement was used in lengths up to 18 inches and little difficulty was encountered.

APPENDIX C



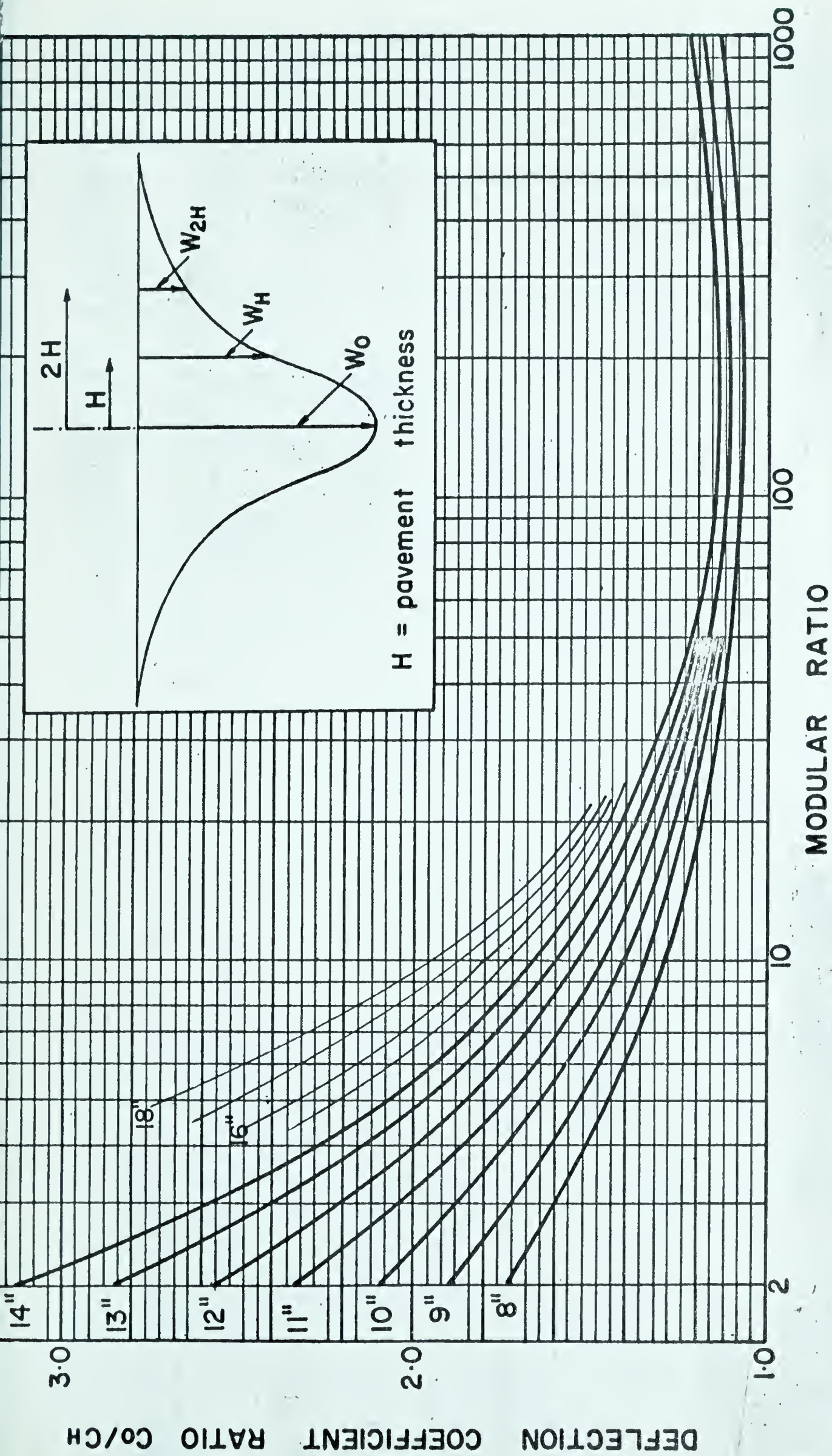


FIGURE C-1: VARIATION OF DEFLECTION COEFFICIENT RATIO C_o/C_h WITH MODULAR RATIO AND PAVEMENT THICKNESS

(FROM SHIELDS, C.G.R.A., 1961)

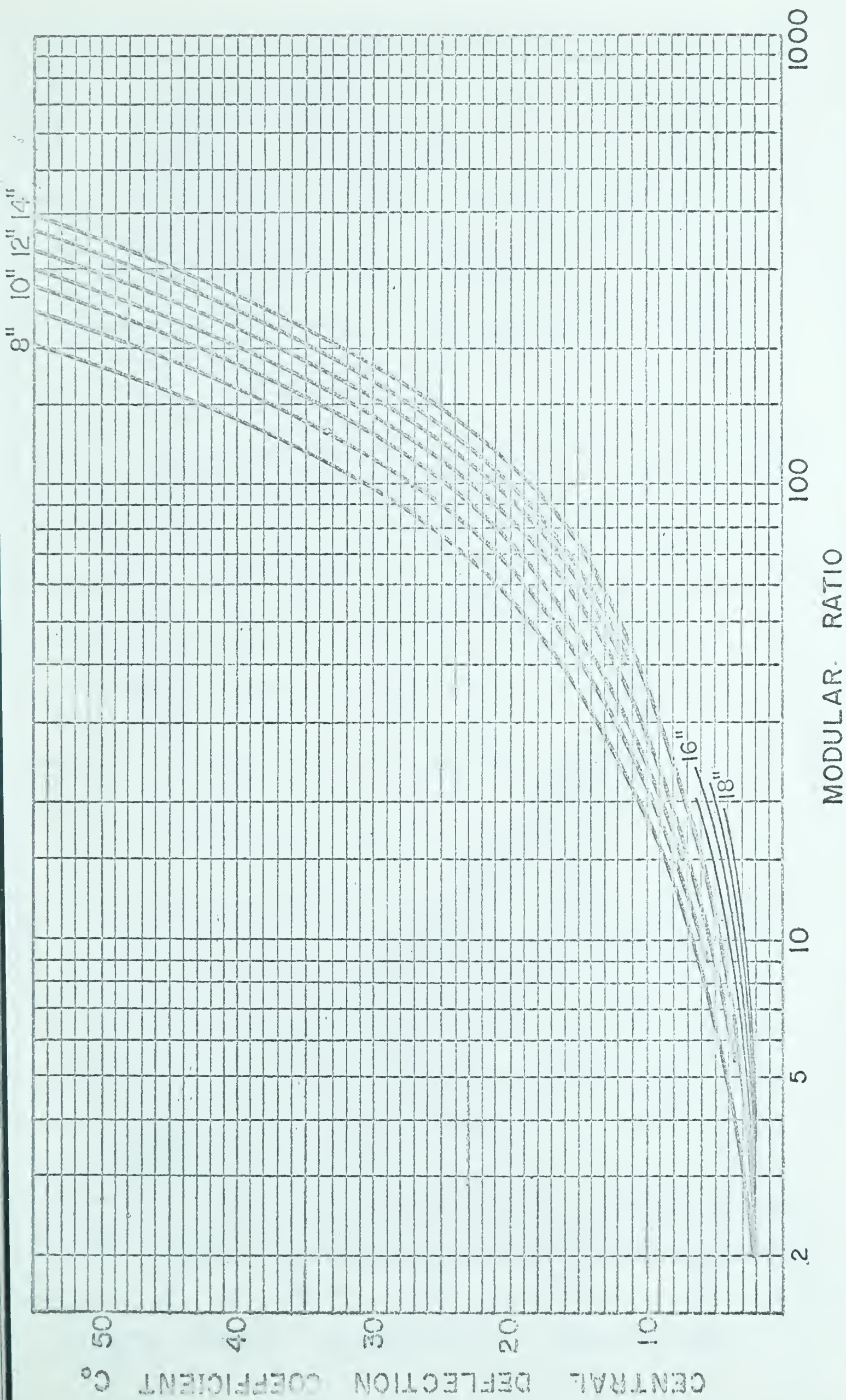


FIGURE C-2: VARIATION OF CENTRAL DEFLECTION COEFFICIENT WITH MODULAR RATIO AND PAVEMENT THICKNESS

(FROM SHIELDS, C.G.R.A., 1961)

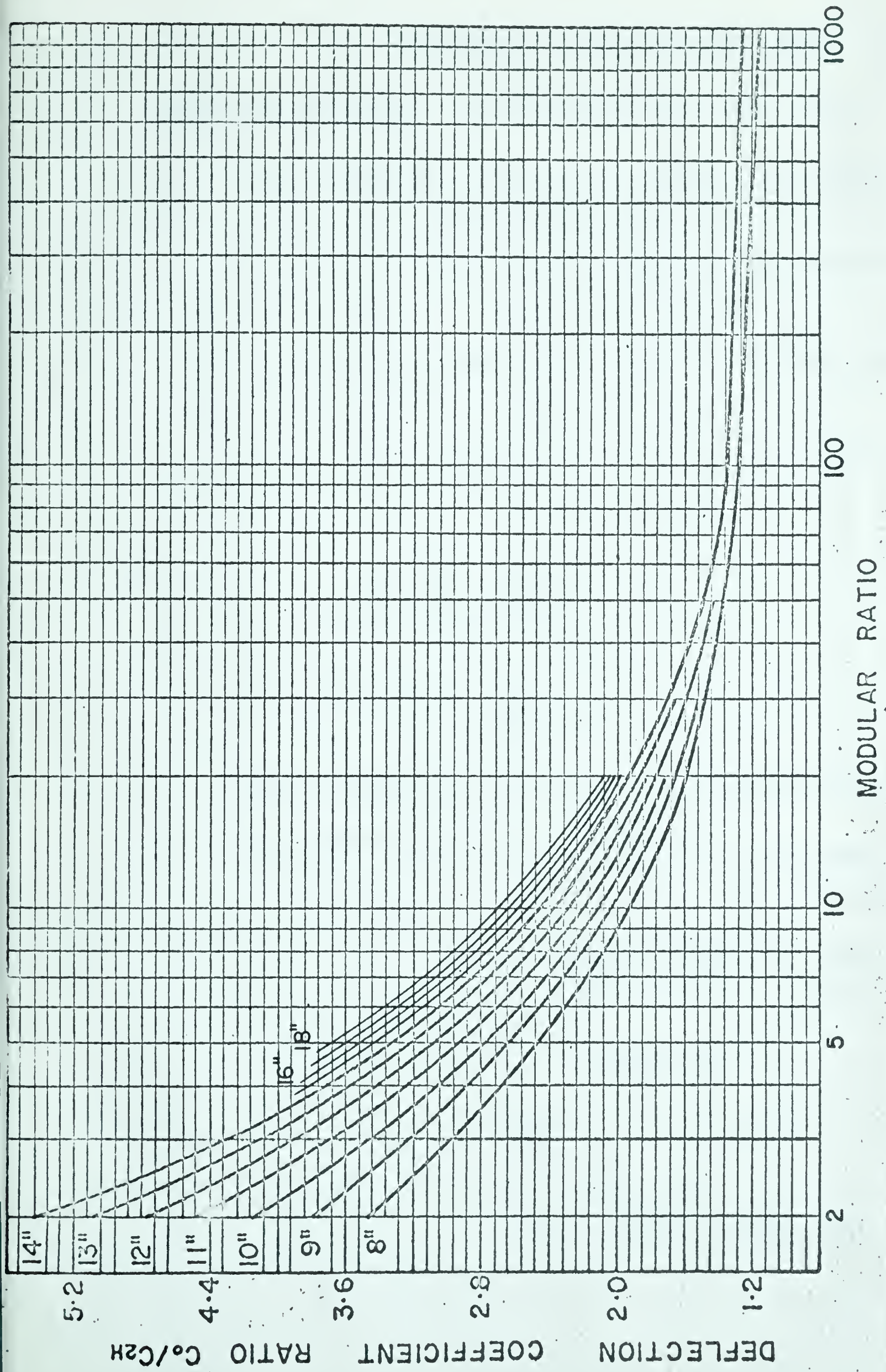


FIGURE C-3: VARIATION OF DEFLECTION COEFFICIENT RATIO C_0/C_{2H} WITH MODULAR RATIO AND PAVEMENT THICKNESS

(FROM SHIELDS, C.G.R.A., 1961)

SAMPLE CALCULATIONS

MODULAR RATIOS : Overlay Structure 39-5/6

From FIGURE 5 : H = structure thickness = 17.4 inches

$$2H = 34.8 \text{ inches}$$

$$\Delta_o = \text{surface deflection at radial distance of } 0 = 27.8 \times 10^{-3} \text{ inches}$$

$$\Delta_H = \text{surface deflection at radial distance of } H = 14.6 \times 10^{-3} \text{ inches}$$

$$\Delta_{2H} = \text{surface deflection at radial distance of } 2H = 7.6 \times 10^{-3} \text{ inches}$$

$$\frac{\Delta_o}{\Delta_H} = \frac{C_o}{C_H} = \frac{27.8}{14.6} = 1.90$$

From FIGURE C-1: $\frac{E_p}{E_s} = 12$

From FIGURE C-2: $C_o = 4.2$ $C_o = \text{central deflection coefficient}$

From EQUATION 3: $E_p = \frac{C_o \times p \times a}{\Delta_o}$ $a = \text{radius of loaded area} = 6 \text{ inches}$

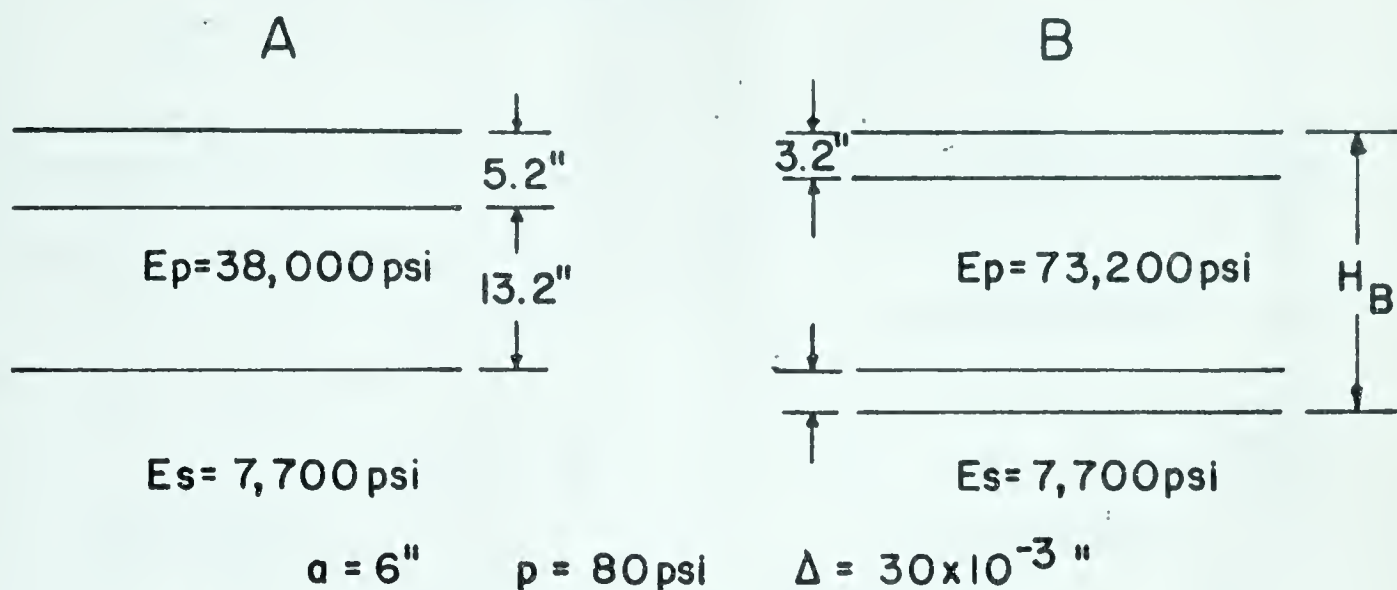
$$= \frac{4.2 \times 80 \times 6}{27.8 \times 10^{-3}} \quad p = \text{intensity of load} = 80 \text{ pounds per square inch}$$

$$= \underline{73,200 \text{ psi}}$$

$$\frac{E_p}{E_s} = 12$$

$$E_s = \frac{73,200}{12} = \underline{6,100 \text{ psi}}$$

GRANULAR EQUIVALENCY OF LOWER BITUMINOUS LAYER



From FIGURE C-2:

$$C_o = \frac{\Delta \times E_p}{p \times a}$$

$$= \frac{30 \times 10^{-3} \times 73.2 \times 10^3}{80 \times 6} = 4.6$$

At $C_o = 4.6$ and $\frac{E_p}{E_s} = \frac{73,200}{7,700} = 9.5$, $H_B = 14''$

Granular equivalency of surface layer: 4:1

Granular equivalency of structure A:

$$(5.2)4 + 13.2 = 34.0''$$

Granular equivalency of lower bituminous layer in B:

$$(3.2)4 + (14 - 5.8) + (2.6)X = 34.0$$

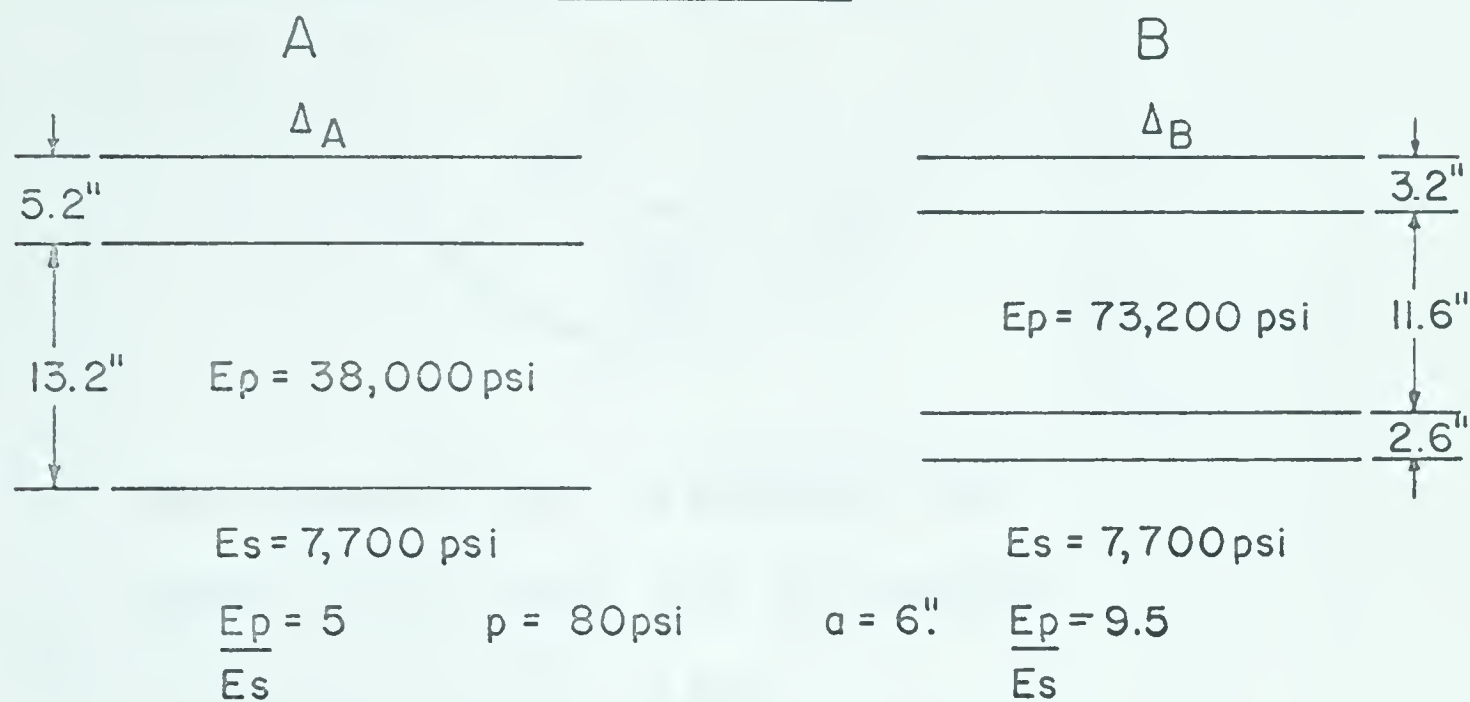
$$X = \underline{5.0}$$

Actual thickness of structure B: 17.4''

Granular equivalency of structure B:

$$(3.2)4 + 17.4 - 5.8 + (2.6)5 = \underline{37.4''}$$

DEFLECTION EQUIVALENCY OF PAVEMENT SYSTEMS



$$C_o = \frac{\Delta \times E_p}{p \times a}$$

From FIGURE C-2: $C_o = 2.6$ at $\frac{E_p}{E_s} = 5$ and $H = 18.4"$

$C_o = 2.8$ at $\frac{E_p}{E_s} = 9.5$ and $H = 17.4"$

Gross deflection of system A:

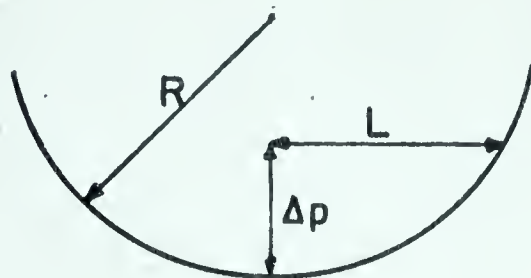
$$\Delta_A = \frac{2.6 \times 80 \times 6}{38,000} = \underline{32.8 \times 10^{-3}"}$$

Gross deflection of system B:

$$\Delta_B = \frac{2.8 \times 80 \times 6}{73,200} = \underline{18.4 \times 10^{-3}"}$$

RADIUS OF CURVATURE

Assume deflection bowl is circular



$$\text{Chord length} = 2L = \sqrt{4(2R\Delta p - \Delta p^2)}$$

Because Δp is small, Δp^2 is negligible

$$L^2 = 2\Delta p R$$

$$R = \frac{L^2}{2\Delta p}$$

$$R(\text{feet}) = \frac{1000 L^2 (\text{inches}^2)}{2 \times 12 \times \Delta p (\text{thousandths of an inch})}$$

$$R = \frac{41.7 L^2}{\Delta p}$$

$$\text{Assume } L = 12 \text{ inches, } R = \frac{6004.8}{\Delta p}$$

Example: surface deflection bowl, FIGURE 5, 39-5/6

$$\Delta p = 0.0088''$$

$$R = \frac{6004.8}{8.8} = \underline{682'}$$

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